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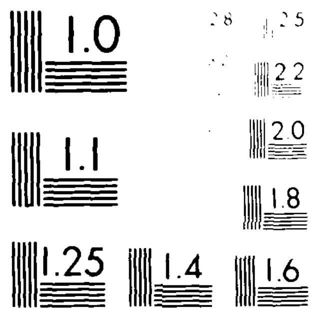
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LEVEL II

2

AN INVESTIGATION INTO THE
PRIORITIZATION OF AIR FORCE
CIVIL ENGINEERING STRUCTURAL
MAINTENANCE DECISIONS

James Long, 2d, Lt, USAF

LSSR 61-81

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This thesis investigated the prioritization of Air Force Civil Engineering structural maintenance decisions. The analysis compared the existing engineering literature on structural deterioration and maintenance with the actual decisions made by Air Force decision makers. The existing engineering on structural maintenance always seems to assume that a decision maker has unlimited resources at his disposal, which is usually not the case with Air Force Civil Engineering. This thesis investigated the relative importance of a range of structural problems and developed scoring models for the prioritization of structural maintenance actions.

LSSR 61-81

AN INVESTIGATION INTO THE PRIORITIZATION OF AIR FORCE CIVIL ENGINEERING STRUCTURAL MAINTENANCE DECISIONS

A Thesis

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

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In Partial Fulfillment of the Requirement for the

Degree of Master of Science in Engineering Management

By

James Long, BS
Second Lieutenant, USAF

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Chapter 1

BACKGROUND

Overview

The U.S. Air Force owns and operates over 136,801 different structures at home and abroad as of FY 1979 (15). Table 1-1 classifies these structures in general categories based on use and facility operating condition. The responsibility for upkeep and maintenance of these structures and their support systems rests with Air Force Civil Engineering whose primary mission is to:

> Acquire, construct, maintain, and operate real property facilities and provide related management, engineering and other work services [34:2].

The variety of structures found in the Air Force's inventory coupled with such factors as age, environmental conditions, construction technique, and intermittant funding causes maintenance and repair to comprise the major share of work handled by Base Civil (BCE) organizations. Special structures such as Aircraft Support Facilities, must be properly maintained by Base Civil Engineering to avoid adverse impacts on mission accomplishment and overall military readiness.

Recurring or preventive maintenance "refers to maintenance performed prior to breakdown [5:592]" and may either

TABLE 1-1

Worldwide Number of Facilities By Category Code And Condition
For Fiscal Year 1979 (Source 15)

CATEGORY CODE	Condition Code 1 (Useable) (Adequate)	Condition Code 2 (Useable) (Substandard)	Condition Code 3 (Force Use) (Substandard)	Condition Code 4 (Sterile)	Condition Code 5 (Unuseable to) (be Disposed)	TOTALS
1XX-XXX (Operational) (And Training)	6,843	960	1,008	349	26	9,186
2XX-XXX (Maintenance) (And Production)	6,062	1,212	1,972	201	35	9,482
3XX-XXX (Research,) (Development) (And Testing)	1,116	113	101	84	1	1,415
4XX-XXX (Supply)	5,264	980	1,242	473	75	8,034
5XX-XXX (Hospital) (And Medical)	427	114	154	9	4	708
6XX-XXX (Administrative)	2,018	599	1,274	102	13	4,006
7XX-XXX (Housing &) (Community)	75,647	13,495	6,219	1,729	291	97,381
8XX-XXX (Utilities) (And Grounds) (Improvement)	5,475	429	390	268	27	6,589
TOTALS	102,852	17,902	12,360	3,215	472	136,801

be minor in nature, such as a simple adjustment, or major, such as a complete overhaul or replacement. Although not very glamorous, preventive or recurring maintenance is an essential function. Significant cost savings can be realized through implementation of recurring maintenance measures when compared to the alternative of letting a facility and its support systems deteriorate to the point where total renovation or replacement is required. Therefore, recurring maintenance actions are imperative if we are to make the most of what we currently have(5:618).

Base Civil Engineering recurring maintenance policies have been designed to:

> Provide an operational installation capable of supporting the mission, including the development and implementation of programs designed to enhance the livability of the base community [34:1-1].

These policies attempt to maximize facility and facility support system life at minimum cost, but because of real life constraints such as money, manpower, equipment, and time they cannot be implemented to their fullest potential.

Often, recurring maintenance work gets done only after emergency and service calls have been completed. During busy periods, recurring maintenance actions are sometimes put on the back shelf, to be done only if the time becomes available. An unconscious or convenience tradeoff takes place. The long-run costs of major overhaul or replacement are chosen over the short-run costs of recurring maintenance measures. This

tradeoff can be dangerous if recurring maintenance actions are not done at all because of the prohibitive costs of major repair or replacement, plus facility down time. If long-run facility costs are to be minimized then the total life cycle cost of maintenance policies -- both intented and actual -- must be considered.

With many competitors for each defense dollar and rising construction costs, the Air Force cannot afford to erect many new buildings. This means that the structures presently in existence should be properly maintained to extend their useful lives. In his keynote address to a tri-service corrosion conference at the Air Force Academy on November 5, 1980, General Bryce Poe II, Commander of Air Force Logistics Command said:

> In an era when our weapons and support systems are so expensive, when production lead times are so extended and when our potential adversary holds considerable numerical advantages in a broad range of systems, the pervasive impact of corrosion must be stopped -- and stopped quickly [14:3].

Furthermore, General Poe stated:

> In this case, a dollar of prevention should prevent a ten dollar cure. We cannot afford to ignore savings of that magnitude -- and we won't [14:3].

The same may be said of the decay and deterioration of Air Force buildings as well.

Thesis Justification

Table 1-2 classifies structures by year and type of construction as of September, 1979. As can be seen from the

TABLE 1-2

Worldwide Facility Totals By Year And Type Of Construction As Of Fiscal Year 1979 (Source 15)

YEAR CONSTRUCTED	BUILDING* TYPE	NUMBER OF BUILDINGS	PERCENT OF TOTAL BUILDINGS
1949 or prior	PERMANENT	10,018	7.3
	SEMI-PERMANENT	5,900	4.3
	TEMPORARY	2,104	1.5
	TOTAL	18,022	13.2
1950 thru 1959	PERMANENT	49,517	36.2
	SEMI-PERMANENT	5,873	4.3
	TEMPORARY	2,492	1.8
	TOTAL	57,882	42.3
1960 thru 1969	PERMANENT	31,391	22.9
	SEMI-PERMANENT	5,252	3.8
	TEMPORARY	2,131	1.6
	TOTAL	38,774	28.3
1970 thru 1979	PERMANENT	17,696	12.9
	SEMI-PERMANENT	2,352	1.7
	TEMPORARY	2,073	1.5
	TOTAL	22,121	16.2
TOTAL WORLDWIDE	—	136,799	100

*Assumed Design Life Is: Permanent - 25 Years
Semi-Permanent - 5-25 Years
Temporary - Less than 5 Years

table, 42.3 percent of the total Air Force inventory was constructed during the period from 1950 to 1959. This means that a large portion of our present facilities are currently entering a phase of their lives where significant maintenance and repair will be needed (21). If these repairs can be identified and accomplished before they become critical to normal facility operations then much money may be saved and down time avoided.

The process of facility decay is an extremely complex one.

> The typical facility as a system exhibits a continuous process of deterioration over time, a complex process in which a large number of interrelated performance characteristics change to produce overall reduced system effectiveness [12:1].

Furthermore:

> Each component of a facility can be expected to affect the mission of the facility depending on the state that the component is in; the states of the component can be expected to have different impacts on the different missions for which a facility may be used.... In many cases, the degradation of the facility mission will be very closely correlated with the effectiveness of the facility as a whole, e.g., the electrical power distribution component in a missile launch facility, while in other cases there may not be a clear-cut relationship (e.g., with the roof component of a warehouse facility) [12:17].

Because deterioration takes place over time a serious question arises as to when maintenance actions should be taken. Maintenance can be done on a periodic basis (generally termed preventive or recurring maintenance) or on an as needed basis.

It is generally agreed that the more money spent on preventive maintenance, the less spent on emergencies and repairs (22:4).

TABLE 1-3

Real Property Maintenance Actual Dollars Spent (Source 18)

YEAR	TOTAL DOLLARS SPENT (IN MILIONS)
1970	315.3
1971	312.3
1972	334.1
1973	374.4
1974	442.9
1975	493.5
1976	425.4
1977	682.8
1978	697.9
1979	714.4
1980	831.2

Table 1-3 shows total actual dollars spent on Air Force real property maintenance (including maintenance, repair, and minor construction) for the last ten years. Although these figures mean little by themselves they do show that maintenance expenditures have been increasing over time and that further increases can be expected in the future whether due to inflation, rising costs, or increased maintenance problems.

Because competition for defense maintenance dollars is fierce and other resources such as manpower, equipment, and time constrained, it is impossible to do all the maintenance that ideally should be done. What can be done instead is to prioritize those structural maintenance actions which if not done result in a reduction of mission readiness and which also result in a significant increase in costs if a facility and its support systems were to fail.

Recurring maintenance can be divided into two major types: (1) equipment and facility support systems, and (2) structural support systems. Equipment and facility support systems include air conditioning and heating systems, electrical systems, plumbing, etc. Structure and structural support systems include roof systems, foundations, and load bearing walls and columns. Because the immediate needs of the customer usually get attention first, Base Civil Engineering organizations spend most of their time maintaining equipment and facility support systems. Structural maintenance, although important to the longevity and safety of a building, usually is done only if extra time and resources are available. What must be done is to prioritize those structural maintenance actions that are most critical to facility life. Then when the time and resources become available for structural maintenance, BCE personnel can concentrate these limited resources on structural items most critical to facility life and mission readiness.

Statement of the Problem

Because of constrained resources Base Civil Engineering organizations cannot do all the recurring, let alone as needed, maintenance that ideally should be done. The maintenance actions that are taken usually deal with equipment and facility support systems while structural maintenance takes a back seat. Often, the structural maintenance that does get done consists of cosmetic and beautification actions (painting, panelling, etc.) while major structural systems such as roofs, walls, and foundations go uninspected. What is needed is some type of structural maintenance prioritization procedures based on the objective of maximizing facility life at the minimum possible life cycle cost. This means that structural maintenance actions should be prioritized according to what specific structural systems (roof, walls, and foundations) and their type of construction (wood, steel, or concrete) are most susceptable to deterioration and hence most critical to the health and safety of a structure.

Statement of Research Objectives

1. Identify what specific structural systems are most critical to overall facility life and readiness.

2. Compare the structural maintenance decisions made by Air Force facility managers to published engineering experience and theory on structural deterioration and maintenance.

3. Develop a prioritization procedure for determining which structural maintenance projects should be done first given restricted maintenance resources.

Thesis Organization

Chapter 1 provided the background necessary for identification and understanding of the problem. Chapter 2, the literature review, will review the concepts of life cycle costing and preventive maintenance and will attempt to relate these concepts to the topic of structural maintenance. Chapter 3, an expanded literature review, will review the engineering principles of structural decay. Chapter 4, methodology, describes the procedure used to test one of the research questions. Chapter 5, data analysis, analyzes the data gathered by the procedures outlined in Chapter 4. Chapter 6, structural maintenance prioritization models, attempts to blend together the concepts presented in the previous chapters through the use of project selection models. Chapter 7 is the research summary, conclusions and recommendations.

Chapter 2

LITERATURE REVIEW

Air Force Regulation 800-11 describes the Life Cycle Cost Management Program.

> The objective of this program is to assure that the Air Force acquires products which satisfy operational needs yet provide the lowest life cycle cost characteristics [31:1].

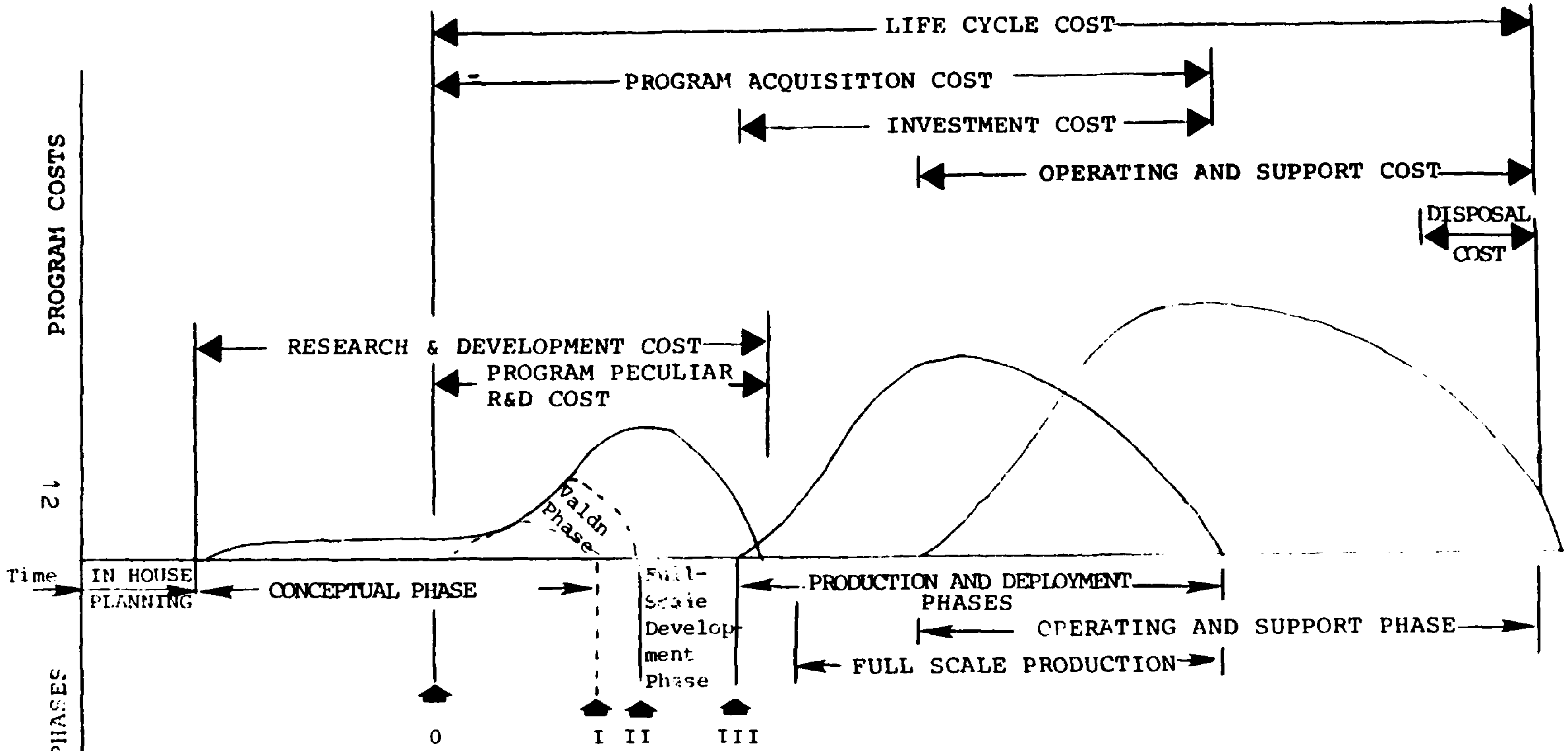
This regulation defines life cycle cost as:

> The total cost of an item or system over its full life. It includes the cost of acquisition, ownership (operation, maintenance, support, etc.) and, where applicable, disposal. To be meaningful, an expression of life cycle elements includes period of time covered, and whether it is intended as a relative expression or absolute expression of expected cost effects [31:1].

The Life Cycle Cost Management Program is a managerial tool that attempts to account for all the costs associated with various investment alternatives with the goal of identifying that alternative that has the lowest long-run cost while still satisfying operational requirements.

Figure 2-1 shows the relationship of life cycle costs to the life of a system. When using life cycle cost techniques to evaluate investment alternatives only relevant and incremental costs should be considered.

> Relevant costs are defined as expected costs which differ under various alternatives [25:12-3].



NOTE - Production and development phases are analagous to building construction and initial modification costs

Fig. 2-1

System Life Cycle Cost (Source 25)

Similarly, incremental costs are defined as additional costs required to achieve a stated capability or level of activity [25:12-3].

Relevant costs are costs that have a definite impact on the selection of an investment alternative. Incremental costs are those costs of an investment alternative that differ from the costs of the current state of the system.

Hundreds of life cycle cost models exist today. No matter what specific model is chosen to represent your system it should exhibit the following characteristics:

1. Completeness - the model should include all the elements of cost which are appropriate for the issue being considered.

2. Validity - the model should represent reality. The analyst must verify the input data to insure the real world environment.

3. Sensitivity - each model should be sensitive to changes to parameters or design. It should be able to show the differences in costs which would occur when system configurations are altered.

4. Availability of Input Data - accurate input data must be available not only to construct the model, but also for meaningful application of the model.

-[25:12-6]

Life cycle costing is basically a procurement and estimating technique that allows for the meaningful analysis of investment alternatives with the objective of meeting some specified cost target.

Life cycle cost techniques have been applied in the analysis of long-run facility costs. Kelley (1977), in a thesis presented to the Naval Postgraduate School, defined building life cycle costs as the:

> ... summation of the total costs which accrue throughout the life of the building, as adjusted for the time value of money to enable useful comparisons to be made. Total costs of a building are recognized as being composed of several elements in addition to initial costs [20:10].

Table 2-1 summarizes the real costs of a building identified in the Kelley thesis. Often facility investment decisions are made solely on the basis of initial cost. Even though these decisions might be economical for the present there is no guarantee that the long-run costs associated with that decision have been minimized. Life cycle cost techniques are essential to building managers because they help identify some of the tradeoffs that take place between initial costs and recurring costs over the long run.

TABLE 2-1

Real Costs of a Building
(adapted from 20)

1. Initial Costs - includes the costs of design, construction, and construction related tasks.
2. Recurring Costs - costs that occur over the life of the building.
    a. Operating-Utility Costs - the costs associated with occupancy and use of a building
    b. Maintenance - the cost of upkeep of the system
    c. Replacement - the cost of replacement of building systems and components
    d. Alterations - the cost of changing the original function of the building
    e. Functional Use Costs - the costs associated with a particular function
3. Total Cost of Ownership - the sum of all costs adjusted for interest effects

Feldman (1975), in his book entitled Building Design for Maintainability, identified eleven factors that must be considered in the selection of a facility maintenance, repair, or replacement alternative. Careful analysis of alternatives using Feldman's framework can identify tradeoffs that affect the life cycle cost of the structure. These factors are:

1. Initial cost
2. Anticipated man-hour savings
3. Anticipated wage rates
4. Anticipated cost of fringe benefits and support costs
5. Comparative life expectancies
6. Cost of money (interest costs)
7. Salvage value
8. Effect on insurance, if any
9. Effect on taxes, if any
10. Effect on depreciation, if any
11. Secondary benefits

-[17:14]

Maintenance costs are recurring costs that can have a great impact on the overall life cycle cost of a structure. Structural maintenance, because of its unglamorous nature and lack of immediacy (no moving parts to break, no lack of power or services, no immediate urgency) is often a forgotten part of overall facility maintenance. If air conditioning or heating systems break down, or there is a loss of electrical power

there is immediate discomfort or inconvenience to the building's occupants and maintenance teams usually respond to these problems first. Structural problems are hidden from the customer's view and are usually taken care of only after other problems have been solved. In a large organization such as the Air Force, structural maintenance problems often take a back seat to other maintenance actions.

Although many times forgotten, structural maintenance can play an important role in extending the life of a building.

> The deterioration and maintenance of engineering structures is a common and serious problem, involving considerable cost and inconvenience to the public [19:1].

Structural maintenance involves two basic aspects: prevention and repair. Preventive action or preventive maintenance can be defined as:

> That action performed to retain an item in satisfactory operational condition by providing systematic inspection, detection, and prevention of incipient failure [30:253].

Repair or corrective maintenance can be defined as:

> That maintenance performed to restore an item to satisfactory condition after a malfunction has caused degradation of the item below specified performance [10:5].

The problem with structural maintenance is that a "malfunction" really means collapse or near collapse of the "equipment" or facility. Often the costs incurred when a facility needs structural repair include not only the repair costs but also the opportunity costs of having the buildings'

occupants do business elsewhere. For some structures housing military operations, the effects on mission readiness can be great.

The overall life cycle cost of maintenance may be significantly reduced through the introduction of preventive maintenance programs. As shown in Figure 2-2, preventive maintenance policies help strike a balance between preventive and corrective maintenance costs with the objective of lowering overall total cost. In general, preventive maintenance procedures are applicable when:

> 1. On a cost tradeoff basis it is more economical to service the equipment while it is still operable (as opposed to letting it run until it breaks down).
>
> 2. The probabilities of component breakdown can be adequately predicted.
>
> -[5:620]

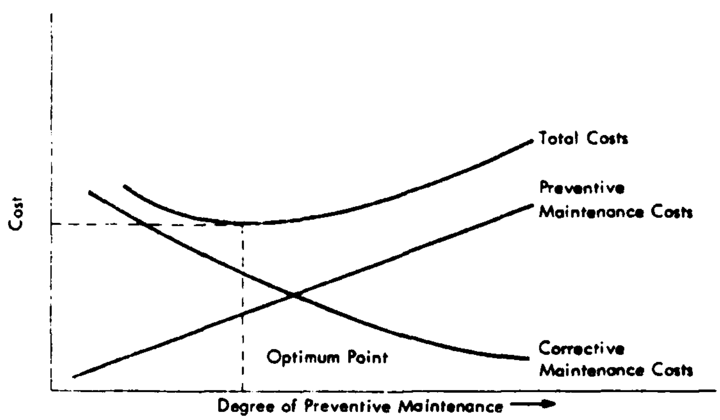


Fig. 2-2

Cost of Preventive Maintenance
(Source 5)

The major problem in applying preventive maintenance techniques to structural maintenance problems is the prediction of when a facility will fail and at what point preventive maintenance measures are warranted. The author feels that of all the hypotheses used to estimate the annual maintenance costs of a facility over its life the U-Shaped Curve Theory is the most accurate. This theory states that maintenance costs are high in the beginning of a facility life because of unforseen problems with the structure (6). These costs then diminish as the structure passes into middle age and then increase during later stages due to deterioration and wearing-out. Basing preventive maintenance measure on the U-Shaped Curve Theory means that preventive maintenance

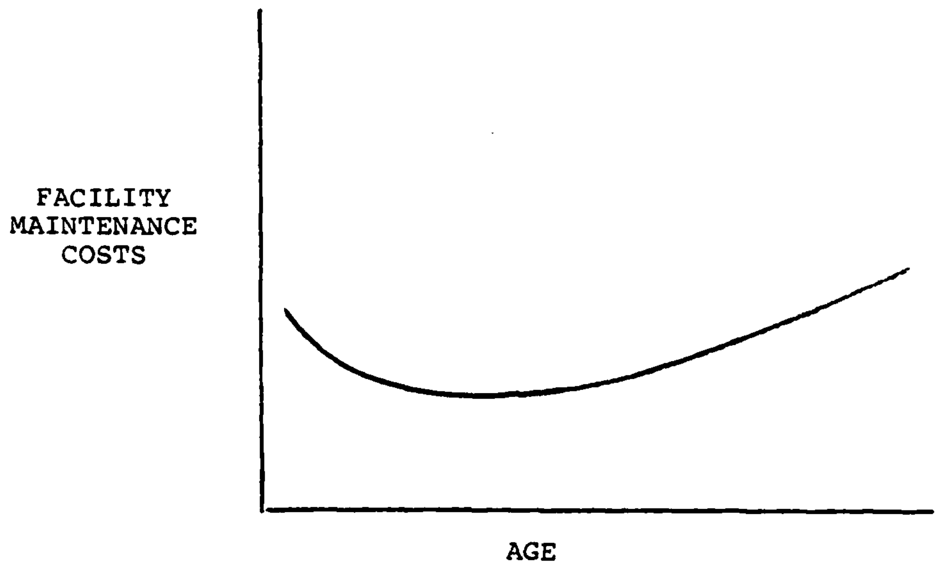


Fig 2-3

U-Shaped Curve Theory (Source 6)

action should be taken sometime around when the structure enters middle age. Extensive preventive maintenance action taken any sooner in the life of the structure is really a waste of money. The structure is new and should not start to deteriorate until a few years later. Only routine inspection should be done before a structure enters middle age.

Before the effects of preventive maintenance measures on life cycle costs of a building can be evaluated the life expectancy of a building must be estimated. Knowing the life expectancy of a wood, steel, or concrete structure helps decision makers in determining what maintenance might be needed to keep a structure safe. Kirby (1973), in a report prepared for the Army Construction Engineering Research Laboratory, identified three measures that can be used to define facility life. These are:

> Physical Life - The time period after which a facility can no longer perform its function because increasing physical deterioration has rendered it useless. Maintenance and repair to prevent deterioration can extend the physical life of a facility indefinitely if there are no cost constraints.
>
> Functional Life - The length of time until the need for the facility no longer exists or until the facility cannot effectively fulfill its original function.
>
> Economic Life - The economic life is exhausted when a financial evaluation indicates that replacement is more economical than retention.

-[21:1]

The physical life of a facility will normally exceed its functional and economic life. Therefore, it is the functional or economic life of a facility that is used in the prediction of when preventive maintenance action is needed. The more accurate the estimate of life expectancy, the better the probability that life cycle costs can be minimized (21).

Maintenance costs over the life of a structure are a function of many variables. Andrews and Joins (1974) in a thesis presented to the Air Force Institute of Technology, identified some of the major variables which influence annual facility maintenance costs (4:12). These variables include:

1. Age
2. Size
3. Functional use
4. Type of construction
5. General facility condition
6. Maintenance policy

One other important variable not mentioned was weather and climate. All of these variables play a significant role in determining maintenance actions and hence the life and cost of a structure.

Andrews and Joins also identified three basic alternatives to facility managers when considering maintenance actions. These alternatives are:

1. Retain the facility as is and continue to maintain it;

2. Rehabilitate the facility -- rehabilitation is defined as bringing the facility up to current standards in terms of construction, layout, and technology; and

3. Replacing the entire facility with an up-to-date, modern, technologically sufficient facility.

-[4:3]

The problem affecting Air Force structural maintenance programs is really two-fold. First, money for maintenance of any kind is hard to obtain. Maintenance money comes only from Congressional appropriations. Therefore, there are real constraints on the amount of maintenance that can be done, structural maintenance being only one part of the entire maintenance picture. Second, the Air Force has in its inventory what can only be termed a "hodgepodge" of facilities. These facilities include a whole array of structure types made of many different materials and of various ages. Air Force manual 88-15 lists three categories of construction applicable to general use structures. These are:

a. Permanent. Permanent construction will be the result of incorporation of the quality and type of materials and equipment, and the details and methods of construction, that will be suitable and appropriate for a building or facility intended to serve a specific purpose and to have a minimum life expectancy of 25 years with normal maintenance.

b. Semipermanent. Semipermanent construction will be the result of incorporation of the quality and type of materials and equipment, details and methods of construction, that results in a building or facility intended to serve a specifc purpose for a limited period of time (less than 25 years and more than 5 years), with a higher than normal degree of maintenance.

c. Temporary. Temporary construction incorporates the type and quality of materials and equipment, and details and methods of construction, that results in a building or facility suitable to provide minimum accommodations at low first cost to serve a specific purpose for a short period of time, 5 years or less, in which the degree of maintenance is not a primary design consideration.

-[33:1-2]

Often, because of changing nature of Air Force mission requirements and budget constraints on new facility construction, structures originally constructed as temporary or semipermanent facilities have been retrofit and modified and are now classified as semipermanent or permanent structures. The sometimes deceptive nature of these facility classifications coupled with a wide range of facility modifications and retrofit activities makes the detection and maintenance of structural problems very difficult.

The Air Force's Recurring Maintenance Program has been developed to help maximize equipment life expectancy and minimize maintenance costs. The purposes of the Recurring Maintenance program are to:

1. Prolong the life expectancy of facilities and equipment.

2. Minimize equipment breakdown and facility emergencies.

3. Sustain reliable support for critical facilities and equipment.

-(11)

This program defines recurring maintenance as:

> Maintenance to real property or real property installed equipment and other items of equipment for which civil engineering has the responsibility. It is work which is pre-identified (in scope) and must be performed at specific repetitive intervals of once a year or more often (except daily), involving facilities, systems, and equipment (11).

The Recurring Maintenance Program is designated to service items whose failure can be accurately predicted. Facility structural systems are inspected regularly according to a set schedule that depends on the type and construction of the facility. But often because of time and money constraints, inspection consists of a cursory glance at structural members located in easily accessable areas and many critical parts of the facility go unnoticed.

A counterpart to the Recurring Maintenance Program is the SMART Concept. SMART is the acronym for Structural Maintenance and Repair Teams. These teams are responsible for items whose breakdown cannot be predicted but warrant immediate attention. The SMART method:

> ... is used to do minor maintenance and repair work in high-use facilities with minimum overhead and time lapse between work identification and work accomplishment. The SMART shop is an actual time accounting cost center that usually works out of a trailer. The crews report directly to the trailer. One or more teams and trailers can be used, depending on the workload [32:6-7].

Because total building replacement is usually not a viable alternative in a military facility cost analysis, recurring maintenance structural inspection teams and SMART

teams can play an important role in extending the life of an existing facility. The detection and subsequent repair of structural problems before they become critical can help minimize the total life cycle cost of that facility by reducing both the frequency and severity of failures.

In practice, structural inspection teams tend to concentrate on cosmetic maintenance. The old addage "out of sight, out of mind" seems to be what happens with overall structural maintenance. The varied nature of the "hodgepodge" of structures currently in the real property inventory coupled with an emphasis on making things "look good" can have serious consequences if structural problems progress too far. If inspection teams can be persuaded to take a little extra time to inspect obscure areas of a structural support system and educated with respect to what problems plague specific structure types then we may better control the life cycle costs of the Air Force's real property inventory. A little time and money now may save us from some truly critical problems later.

Chapter 3

STRUCTURAL MAINTENANCE THEORY AND CASE HISTORIES

Introduction

This chapter will review the basic principles of the deterioration and maintenance of the three main types of construction materials (wood, steel, and concrete) found in Air Force structures. Some case histories will also be presented and analyzed to illustrate how preventive maintenance policies, if applied throughout the life cycle of a structure, can save money and keep a structure in excellent physical condition. It is the natural processes of decay, deterioration, and disintegration of structural systems that will be investigated in this chapter. Structural problems evolving from design errors, foundation (soil) failures, and overloads will not be covered directly although many of these factors interact with poor maintenance policies to produce unsafe structures.

No construction material is completely immune to chemical, physical, or biological attack. However, when structural problems do arise, it is often difficult to attribute the cause to one specific aggressor. It is the interaction of many factors that determines the integrity of structural

systems. Therefore, broad and flexible maintenance policies are needed to detect and remedy minor structural problems before they progress into major problems that endanger the life span and safety of a structure.

Timber Structures

The American Institute of Timber Construction states that when designing timber structures for permanence:

> Permanent timber structures should be built not only to be structurally adequate but also to be durable with a minimum of maintenance. With proper design, construction, and usage, wood is a permanent construction material. Certain conditions affect durability and maintenance costs. If proper consideration is given them in the design phases of a project, there will be greater assurance that the structure will be durable and the maintenance costs will be low [2:1-7].

What is actually implied by the above statement is that the life cycle costs of a timber structure should be considered during the design phase. Life cycle costing is an excellent concept for reducing the long run costs if applied from the birth to death of a structure. Such has not been the case with most of the Air Force's timber structures.

Many of the timber structures presently in the Air Force's and other Defense Department organizations inventories were erected during World War II and were designed to have a useful life of only a few years. Because of support for the war effort, designers were forced to use local indigenous woods whose quality was often less then the previously available commercial grades of timber. Hence, the term "birchwood

hangers" evolved to describe some of the aircraft facilities that were built during this era. Because these structures were designed for only a short life span and resources were short during the war years many were not initially treated for decay resistance. Many of these structures are still in use today and are close to being thirty-five or more years old.

Maintenance of these World War II vintage timber structures can only be described as haphazard at best. The condition of such structures varies from region to region and maintenance is really a function of whether or not those involved in maintenance decision making have knowledge of the specific needs and problems of timber structures. Because timber is a biological material many special precautions must be taken to prevent deterioration. The following discussions will present a review of the major problems encountered when attempting to design and maintain timber structures for permanence.

Timber Decay

Timber decay, commonly termed "dry rot", is caused by microscopic organisims called fungi that consume the wood as food. The term "dry rot" is actually a misnomer because fungi need some source of moisture in order to grow. These organisms cause a breakdown of the cellular structure that gives wood its strength.

> The symptoms are a softening and discoloration of the wood, and fluffy or cottony appearance, destruction of the cells, and, in advanced stages, the appearance of fruiting bodies in the form of mushrooms and encrustations [19:238].

Later stages of decay not only affect the strength of the timber but also its fire resistance.

For growth the fungi need the proper combination of food, water, air, and temperature. Control or elimination of any one of these essential elements inhibits the growth of the fungi. Elimination or deprivation of these essential elements must be permanent because:

> ... the spores of the fungi may be dormant and undetected in the wood for many years, returning to activity when conditions become favorable [19:239].

The prevention and treatment of timber decay falls into five major categories (19).

1. Deprivation of moisture.
2. Deprivation of air.
3. Use of decay resistant species.
4. Preservative treatments.
5. Construction practices.

One way to assure against decay is to build with high grade seasoned timber. Properly seasoned timber has a moisture content that is twenty percent or less and is usually resistant to fungus attack (29). But, good grade timber alone will not assure against decay. Proper site drainage along with ventilation and condensation control must be

provided in order to maintain the timber's moisture content at or below the twenty percent level. In short, all attempts should be made to keep the wood as dry as possible.

The deprivation of air, although possible in theory, is rather difficult to achieve in practice. Unless the timber is coated with a heavy bituminous or concrete covering air will still be present in sufficient quantities to support fungus growth. Painting alone will not insure that air will be shut off. The only instance where air can be cut off effectively is where the timber is buried at depths greater than five or six feet for granular (sands and gravels) soils and at shallower depths for fine grained (silts and clays) soils. At these depths the supply of air becomes the limiting factor for growth (19).

The use of decay resistant species is another method that is possible in theory but again hard to achieve in practice. The heartwood or inner dead layers of growth of a tree has a natural ability to resist decay. The sapwood or outer living layers of growth are rich in sugars, moisture, and other factors favorable for the growth of fungus. However, it is extremely difficult and would be prohibitively expensive to separate the heartwood from the sapwood. Sawn timber will inevitably have both types of wood. Therefore, this method of decay resistance is extremely unreliable and other preventive measures should be taken to insure against decay.

Preservative treatment is one of the most widely used methods to protect wood from decay. Standards for wood preservation can be obtained from the American Wood-Preservers Association (3). The treatments make the wood, which is the food for the fungus, poisonous and hence unsuitable for attack. Preservative treatments fall into three main categories:

1. Waterborne preservative
2. Fortified petroleum oils
3. Creosote

Waterborne preservatives treat the timber with a solution of water and metallic salts. This type of preservative treatment is used where architectural considerations are important because these treatments leave the surface of the wood relatively clean and odor free. Also, paint can be applied to the wood after this type of treatment. However, these metallic salts, because they are water soluable, are subject to leeching and treatment may have to be performed again at some specified interval.

Fortified petroleum oils, like waterborne preservatives, are used where architectural conditions govern preservative selection. The third type of wood preservation, treatment with creosote, has given the best overall results. Unlike waterborne and fortified petroleum oil treatments, creosote or coal tar is also effective against wood destroying insects as well as fungus. Creosote has a very low solubility

in water and therefore resists leeching. It has a relatively low cost and has a good track record. However, there are some disadvantages. Creosote when first applied is volatile and may present a fire hazard. Also, creosoted surfaces cannot be subsequently painted and its odor may be objectionable if used in places frequented by people.

One of the easiest but forgotten principles of decay prevention is construction site control. What this means is to keep the construction site and subsequent home of a structure free from extraneous material that might be subject to decay. In practice what this means is to keep your structure free from debris and abandoned lumber.

Insect Attack

In many regions, attack by insects can be a very serious problem if not properly detected and controlled. Insect damage can be grouped into two major categories:

1. Those insects that consume to wood as food
2. Those insects that burrow into the wood for protection, reproduction, etc. without consuming the wood as food.

Probably the most well-known of the wood consuming insects is the termite. Over 1,500 species of termites have been identified (23). There are two major classifications of termites based upon behaviorial characteristics: wood inhabiting and earth inhabiting. Wood inhabiting termites develop

colonies that are almost entirely confined to wood. Earth inhabiting or subterranean termites, on the other hand, develop colonies that survive both in soil and in wood. Although both groups can cause damage, it is the earth inhabiting group that commonly causes the most problems. This group tunnels from the earth into the timber to establish colonies and to find food. The wood inhabiting group rarely enters the soil and usually lives its entire life in the same piece of timber or other nearby members.

Other wood consuming insects include a group commonly termed powder post beetles. These beetles burrow into and consume the wood reducing it to a fine powder. This group is second only to termites in their ability to destroy timber structures. Many other groups of wood consuming insects are known but none do as much damage as termites or powder post beetles.

The second type of damage is caused by insects that burrow into the wood for shelter, reproduction, etc. while not actually eating the wood. This group includes marine borers, carpenter ants and bees, and engraver beetles. These insects burrow into the wood and create void spaces that greatly reduce the strength of the timber. As the organism grows it also increases the size of its burrows thus contributing more and more to the degradation of a structure.

The prevention and treatment of insect attacks falls into two major categories (19):

1. Keep wood away from insects.

2. Poisoning of the wood or surrounding environment.

Keeping the wood away from insects involves separating the wood from the ground, preferrably a distance of twelve inches or more. Essentially, these precautions are the same as for preventing the decay of timber. Poisoning of the wood with creosote provides excellent protection against both decay and insect attack. Additional protection can be achieved through poisoning of the soil and foundation of a structure to create a barrier against attack. The best assurance against insect attack is to consult your local building officials to see if there have been any problems in the past. Many local insect problems exist and can only be evaluated on a case by case basis. What is important to remember is that insects can seriously damage timber structures if the proper precautions are not taken and that inspections must be performed on a recurring basis to detect any insect activity.

Shrinkage Problems

Because timber is a biological material it is subject to shrinkage and swelling that are functions of the surrounding air temperature and humidity.

> This shrinkage causes bolts to loosen; creates splits and checks; and as a result of the loosened connections, causes deflection of members and distortion and weakening of assemblies [19:271].

Checking or splitting is caused by a difference in the moisture content of the wood. As wood seasons the outer layers dry out first while the inner layers remain relatively moist. As drying or seasoning progresses, stresses build up in the wood and are relived when a split or check occurs.

In many cases splits or checks (radial cracks) do not greatly affect the overall strength of the wood but again these defects must be evaluated on a case by case bases. Often splits occur right through bolt holes which render the bolt eventually useless. Shrinkage of the wood also causes bolt holes to widen thus loosening the connections and contributing to excess deflections (19).

Splitting, checking, and the enlargement of bolt holes is almost impossible to prevent. What must be done instead is to inspect timber structures on a regular basis for the above problems. Loose bolts can be tightened, split members can be mended or replaced, and structural integrity restored once the problems are located. What must be kept in mind is that timber is sensitive to many environmental factors that do not affect other construction materials as quickly as they affect timber structures.

Deterioration of Hardware

A problem that often accompanies the enlargement of bolt holes is the deterioration of the hardware used to fasten together timber members. As the bolt holes enlarge moisture is allowed to get in causing corrosion. Corrosion also

occurs on the bolt head and nut. In marine structures the corrosion problem is compounded by the presence of salts that further aggravate tne corrosion process. Prevention of hardware corrosion is virtually impossible. Good control of corrosion, however, can be obtained by using hardware that has been specially made or galvanized to resist corrosion. Also, the amount of hardware that is exposed to the atmosphere should be reduced. Again, because corrosion cannot be totally prevented, proper inspection schedules must be set up and followed to insure that the hardware is sound and not endangering the safety of a structure.

Some Timber Structure Problem Case Histories

In 1975, the timber roof trusses of building number 942 at Norton AFB, California were inspected for structural soundness. The conclusions of the architect-engineers preliminary report were as follows:

> Based on the existing need for replacement of members, alignment of trusses, tightening bolts and any repair required due to deteriorated or altered members, it is our opinion that these trusses are borderline in meeting minimum safety standards during any extreme conditions until after repairs have been accomplished. It is strongly advised that a periodic maintenance program for tightening of bolts and repairing of members in all trusses and other structural parts of the building be initiated. The period for accomplishing this work should not exceed a one year interval [8:2].

This case illustrates how timber problems tend to be interrelated. Loose bolts and deteriorated members have

caused the trusses to deflect and become misaligned. The trusses are just barely meeting minimum safety requirements. A periodic maintenance program has been suggested to help keep ahead of timber problems in the future and to maximize building safety at a minimum cost.

Another structural timber problem occurred in four aircraft hangars at Seymour Johnson AFB, North Carolina. The hangars in question were erected sometime in 1942. The engineers' final structural and cost analysis report dated 31 December 1975, estimated that the present cost of maintenance and repairs needed to bring the hangars up to standards totalled $4,285,930. The report stated:

> Economic justification for replacement or repairs of the building is governed by planned operations and use of the facility over the next five years. It is the opinion of this office that replacement or abandonment of the facilities will be eventually required. Provision of recommended repairs should prolong the life of the safe occupancy of the building for five years assuming an increased rate of deterioration does not occur. However, it must be assumed that the deterioration will continue at some rate. Only continued observation can determine what that rate of deterioration will be and consequently the future useful life of the structure /9:23/.

Deterioration of the timber coupled with the loosening of bolts due to shrinkage has caused excessive deflections in these hangars. Had some periodic bolt tightening and maintenance program been adhered to throughout the life of these structures, the high cost of repairs and the possible exorbitant costs of replacement could have been lessened and quite possibly avoided (2).

Deterioration of the glue laminated wood arches of hangars 75 and 79 of the U.S. Coast Guard Repair and Supply Center, North Carolina was repaired in 1977 using an epoxy grouting method. "Hangars 75 and 79 were built during World War II and are presently utilized as the Coast Guard's only major aircraft overhaul and repair facility /26:1/." The total cost of repairs was approximately $360,000 (1979 dollars).

Deterioration of the glue laminated arches was attributed to roof leaks and subsequent fungus attack that went unnoticed for a long period of time.

> The investigation of the condition of the arches revealed that the most significant widespread deficiency of the arches was wood decay caused by leaking of the roofing and flashing over the years (roof repairs were accomplished in the previous year). However, there also existed some minor insect damage, fire damage, and delamination of the arches /26:1/.

A point that must also be considered in this case is that because of the very specific uses of the structure there would have been an extremely great opportunity cost had this deterioration progressed to the point where the structure became unusable forcing the Coast Guard to overhaul its aircraft elsewhere. Again, a periodic and thorough inspection of the timber structures is essential to assure the long life and safety of a timber structure.

Steel Structures

Although many different types of steel and alloys have been developed for long life, deterioration can still be a serious problem given the right exposure conditions. Because steel is a common structural material, knowledge of how it deteriorates is essential in determining the maintenance actions needed to protect a structure.

Corrosion

Corrosion, more widely termed rust, is the most prevalent form of steel deterioration.

> Corrosion may be defined as the conversion of metals, by natural agencies, into compound forms and is, by far, the major maintenance problem in steel structures. Deterioration due to this agent may be readily distinguished. The symptoms are a pitted, oxidized surface, usually showing loose flakes or scales of oxide and a typically reddish-brown rust-colored appearance /19:20/.

Corrosion is a very complicated and intricate process whose nature is beyond the scope of this report. What is important, however, is that corrosion can be minimized. The following are important steps that can help minimize corrosion:

1. Keep the steel clean and free from debris.
2. Protective coatings.
3. Avoidance of galvanic couples.
4. Introduction of galvanic protection.

Keeping the steel clean is a very simple yet important step. Dirt and debris have the capacity to absorb moisture which is a critical ingredient in the corrosion process. Dirt, dust

and other particles may also contain minerals and compounds that further aggravate corrosion. A thick layer of dirt and dust over steel does not constitute a protective layer.

The most common type of protective coating is paint (19). Painting isolates the steel from hazardous environments and provides a layer that is itself consumed rather than the steel when attacked. The technology of paints and coatings is a science in itself. Coating types include bituminous paints, zinc layers, alkyd paints and many others.

A cousin to the theory of protective coating is encasement. Encasement is the protection of steel structural members by embedding them in a protective layer of concrete or bituminous material. Encasement is most often used where steel is to be in contact with seawater or highly corrosive soils.

The avoidance of galvanic couples entails using materials that, when placed together in contact, do not form anodic and cathodic reactions. Simply stated this means avoidance of the "brass bolt-steel washer" pitfall. Designing with similar metals is recommended but often difficult to achieve when doing a repair job. What must be remembered is that if different metals are used there is potential for one to become an anode and the other a cathode. The anode will corrode away depositing much of its transferred material on the cathode.

Galvanic protection uses the principle of galvanic couples by creating a sacrificial anode which has been

specifically designed to corrode instead of the steel. This procedure has a distinct advantage in that the spent anode can be replaced quite easily and replacement can be included in maintenance schedules. This type of protection is most often used where steel is in contact with the ground or is in direct contact with a large volume of water.

Abrasion

Abrasion or erosion of steel structures:

> ... also may be readily identified and may be easily distinguished from deterioration due to corrosion - by the worn smooth appearance of the abraded surface [19:23].

Abrasion may also have occured and corrosion subsequently takes over. In many instances it is difficult to determine whether corrosion or abrasion is the exact cause of the trouble.

Abrasion is caused by the physical wearing action of some agent on the steel. This agent may be another steel member, sand or dirt in combination with wind, and fluid wave action. Abrasion is most frequently encountered in marine or desert environments: really any site where the action of the water or wind in combination with a granular soil can initiate a sandblast or grinding process on the steel.

The best measures for protecting against abrasion is either by encasement or armoring. Encasement is the embedding of steel in some protective sheath, concrete for instance. Armoring, similarly, is the use of protective devices (iron

plates, claddings, etc.) to bear the main thrust of the abrasive forces. The protective device should be designed to deflect most of the abrasive material around the steel itself. Thus, it is important that the rest of the steel structure, behind the plates or cladding, be streamlined.

Loosening of Connections

Once the corrosion or abrasion of steel has started the loosening of bolts and joints usually follows. Corrosion, especially of bolts and bolt holes, causes excessive deflections and stress concentrations that may be extremely dangerous. Deflections in themselves may or may not be dangerous but are usually the symptom of some other structural problem. Where large live loads are present loose connections may be a precussor to failure by fatigue.

The prevention of loose connections is closely associated with the prevention of corrosion or abrasion. Proper adherence to the principle of corrosion prevention is an excellent way in which to minimize structural problems due to loose connections. Also, the use of high-strength corrosion resistant bolts can help minimize connection problems.

Fatigue and Impact

Fatigue is defined as:

> ... the fracture of a structural member due to repetitive, fluctuating load occuring at stresses at or below usual allowable design values [19:24].

Fatigue occurs in structures whose live load to dead load ratio is very large. Impact damage, on the other hand, is damage done to structural members due to moving objects.

> Impact damage is characterized by local distortion of the affected member, usually in the form of a crimp or a bow of short wavelength /19:24/.

Crimped members should be investigated thoroughly to see if the damage present was caused by impact or by buckling. Buckling is a more serious structural problem that may only be remedied by design changes.

Prevention of fatigue is accomplished by ensuring that structures supporting large amounts of repetitive live loads (highway bridges, machinery supports, etc.) are not being overstressed and are in the best possible physical condition. Prevention of impact damage entails the armoring of structural members subject to possible impact by moving loads. In these cases the armoring absorbs most of the impact force while the structural member remains intact.

Some Steel Structure Problem Case Histories

Steel, if not properly protected, will corrode and be continuously reduced in section. Often the corrosion is worse in areas not externally visible.

> A 44-year old roof in Brooklyn, NY, collapsed in 1965. The building started as a movie house and was converted to a supermarket without altering the roof. Five steel bowstring trusses projected above the roof, which was a concrete slab encasing the flat bottom chords. Roofing was pitch-pocketed

> around the lower ends of the vertical and diagonal web members; the rest of the trusses were painted. Moisture filtered down the contact between the steel and the pitch and seriously corroded the invisible steel. The painted steel was in good condition. The entire roof collapsed with a crash and air shock then blew out the street windows. Luckily the 50 occupants escaped with only a few minor injuries [16:243].

A medium span rolling lift bridge suffered damage due to corrosion and impact.

> Heavy corrosive attack occurred in several locations. The stiffeners and bottom flanges of the track girders of the fixed span were heavily attacked, the outstanding legs of the bearing stiffeners being entirely corroded through. This corrosion was due to an accumulation of dirt, leaves, and debris on the shelf formed by the bottom flanges of the girders. The accumulation acted like a sponge to retain water, thereby hastening deterioration [19:51].

Corrosion occured in the very places that were susceptable to attack. Also, debris probably accelerated the rate of corrosion by providing a constant supply of water.

Concrete Structures

> Concrete can be considered to be an artificial stone made by binding together particles of some inert material with a paste made of cement and water. These inert materials are the aggregate. Among the materials used for this purpose are sand, gravel, crushed stone, air-cooled blast furnace slag, expanded clay, shale, slate and slag, vermiculite, perlite, pumice, scoria and distomite, basite, limonite, magnetite, hematite, and iron and steel punchings [27:83].

Not only does the strength and durability of concrete depend on the quality of aggregrate used but also on the quality and type of cement used, construction practices, design practices, and the environment in which the concrete will

live. Because concrete is such a complex composite material, basic understanding of some of its more frequent maintenance problems is essential to ensuring the life expectancy and safety of a structure made wholly or partially of concrete.

Physical Aggression to Concrete

Physical aggression to concrete includes freeze-thaw action, abrasion, temperature shock, and absorption of moisture by the concrete. Freeze-thaw action causes the outer surfaces of a concrete structure to scale.

> This disruption of the concrete surface is caused by the penetration of the surface layers by moisture when this is followed by sub-zero temperatures. The consequent freezing and expansion of the water absorbed in the concrete can cause disintegration of the surface layers [24:30].

Prevention of damage due to freeze-thaw action and the absorption of water usually involves one or more of the following:

1. Design of the structure to minimize exposure to moisture.
2. Low water-cement ratio.
3. Air entrainment
4. Suitable materials.
5. Adequate curing.
6. Special attention to construction practices.

-(1:6)

Abrasion, as was the case with a steel structure, is the wearing away of material by rubbing and friction. Abrasion of concrete occurs on floors, pavements, and in concrete

storage bins or hoppers. Wind and water carrying fine particles of granular material can also cause damage. The prevention of abrasion where wind or waterborne particles are the cause usually entails encasement or armoring. Abrasion of floors, pavements, and other high-use surfaces usually depends on how a surface was finished during construction. Abrasion resistance can also be affected by:

> ... the use of high-strength concrete, smooth, dense surfaces; air entrainment; curing; and delayed finishing ... [19:85].

Temperature shock results from variations in the temperature of hardened concrete due to changes in atmospheric and ground conditions. Changes in atmospheric temperature causes warping stresses to build up in concrete, especially slabs on grade, that can cause severe cracking that sets the stage for further deterioration by chemical attack. Variations in concrete temperature may also be due to normal use conditions of the concrete such as in dams, machinery footings, and other mass concrete structures.

Prevention of deterioration due to temperature shock entails using proper construction practices and mix design while also providing steel temperature reinforcement and joints where applicable. The use of temperature resistant aggregrates is also suggested. Good design practices allow for expansion--contraction of the concrete and include measures to relieve stresses caused by temperature. Also, keeping water away from the concrete is recommended to minimize the chances of damage by freezing water.

Chemical Aggression

The chemical aggression of concrete can be divided into two broad categories: the chemical attack on the concrete itself and the chemical attack on reinforcing steel. The chemical attack on concrete usually occurs from acid soils or waters, the use of deicing chemicals, corrosive chemicals, and bacterial action. These chemical agents dissolve and destroy the cement and sometimes the aggregrates. Chemical attack is further aggravated when undesirable or inferior materials have been used in the cement mix. Also, salt water, if used to make cement, greatly lowers the ability of the concrete to resist attack. The use of salt water for mixing cement is strongly discouraged (24).

The prevention of chemical attack on the concrete itself is best accomplished by controlling the mix design. If the use of deicing chemicals is anticipated or acid water runoff from acidic soils is a potential hazard then these situations should be addressed during the design phase. A sulfate resistant cement should be used in high sulfate situations while a cement with a limestone aggregrate will help in neutralizing acid attack. When use of a chemical resistant cement is not enough, special coatings and liners can be used to produce a protective barrier against attack.

When inspecting for chemical attack, one should clearly scrutinize the natural or manmade channels where water runoff occurs. Many times these out of the way footings, supports,

or connections are where attack goes unnoticed unless one is specifically looking at these areas. Deterioration of these components is critical because as these components crumble away stresses build up in remaining sound material that could seriously endanger the overall safety of the structure.

The second type or class of chemical aggression is attack of the reinforcing metal. The corrosion of reinforcing steel is similar to the corrosion of hardware in timber structures except for the fact that the corroded steel is constrained by the surrounding concrete.

> The volume of the oxide produced by corrosion is about eight times that of the parent metal ... [19:68].

Thus, as steel corrodes it expands in volume creating stresses that can ultimately cause cracking and spalling of the concrete.

Prevention of chemical attack of reinforcing steel entails keeping the steel away from corrosive agents. This means ensuring that the reinforcing steel is adequately covered by concrete and that water is kept away, as much as possible, from the structure. Consultation of the American Concrete Institute building code is recommended for determining the minimum concrete cover over reinforcing bars for different exposure conditions.

Deterioration Due to Improper Construction Operations

Because concrete is such a complex construction material, proper care must be taken during pouring, curing, and finishing to insure that the final product will be of the utmost quality. Problems that occur due to improper construction practices include drying and settling shrinkage, local subgrade settlement, and improper curing procedures.

The prevention of deterioration due to improper construction practices requires that frequent inspections of the materials and work be done. Contracts should be written with the specifications and method of construction desired put in clear, concise terms. Financial and legal responsibility for not adhereing to contract specifications should also be addressed. Because of various techniques and methods of placing concrete it is almost impossible to specify one best way to prevent deterioration or defects. Instead consideration should be given to a few brief but extremely important principles of concrete work.

1. Insure that proper subgrade and subbase preparation, compaction and stabilization has been completed.

2. Make certain that efficient drainage facilities have been installed to carry water away from the concrete.

3. Use of proper vibratory and finishing equipment is essential to long lasting concrete structures.

4. Proper curing procedures must be followed or serious problems will develop early in the life of the structure.

The proper construction practice must be tailored to meet the needs and future use of the structure. Because of the wide and varied uses of concrete there is no one best way for proper construction and finishing but no matter what technique is used it must follow closely to specifications set forth by the American Concrete Institute and other professional concrete organizations(1).

Some Concrete Structure Problem Case Histories

Chemical attack on the cement, aggregrates, and imbedded steel can be a serious problem. Chlorides are probably the most common damage causing agents.

> Chemical substances other then the chlorides will also rapidly oxidize the imbedded steel, as shown in the 1956 breakup of precast beams exposed to the warm moist air in the lumber drying kilns at Muskegon, Michigan. The rust formation in the steel bars started slippage from reduction in bond resistance and shear failures occurred near the ends of the beams. Beams with serious distress were replaced and all concrete was given a seal coat of asphaltic water proofing [16:277].

Chemicals in the soil can also cause deterioration.

> An investigation of concrete deterioration of a foundation for a silo in Copenhaver Harbor in 1957 indicated sulfate attack by the ground water with aggressive carbon dioxide, also a primary agent of disintegration. Excessive formation of secondary chemical deposits were found in the concrete exposed to ground water [16:255].

Proper control of the concrete mix is essential for sound structures. In 1963 the city of New York ordered the entire removal of concrete used in construction of Public

School 90 in Brooklyn because the twenty-eight day strength was forty percent below the specified 3500 PSI design strength for lightweight concrete.

> Much of the concreting had been performed in cold weather and an inspection of the mixing plant, correlated with analysis of the concrete cores, indicated that the aggregrate had been piled without protection, contained much ice and was completely uncontrolled as far as separation of sizes was concerned [16:248].

Summary

From the previous discussions and case histories on structural deterioration it is evident that timber is an extremely environmentally sensitive construction material. Therefore, from a maintenance standpoint timber is more difficult to maintain than either steel or concrete. Timber deterioration takes place throughout the section of a member. In contrast, steel and concrete deterioration takes place at the surface and gradually works its way inward.

Whether steel or concrete is the second most difficult material to maintain is hard to determine. Assuming that the concrete has been properly mixed and cured (many problems with concrete structures have their origin in the mix design or curing processes) it becomes a relatively inert material. Therefore, based on the engineering principles of decay and given proper construction practices for concrete, steel is generally the second worst construction material to maintain. Improperly

mixed and cured concrete can be a maintenance headache much worse than timber but given proper construction practices maintenance difficulty is usually in the following order:

1. Timber (most difficult)
2. Steel
3. Concrete (least difficult)

Chapter 4

METHODOLOGY

Design of Test

A survey was designed to test the research question concerned with the prioritization of structural maintenance actions. A sample survey can be found in Appendix A. Nine major structural systems were identified by the survey. These major structural systems were very general in describing the components of a building. Problems pertaining to general structural systems rather than problems with specific structural components were used in the survey because the wide and varied range of structures found in the Air Force's inventory would have made the list of specific structural component problems too long to be manageable for the objectives of this thesis. It was felt by the author that broad, general categories of structural components would capture most of the problems, both general and specific, found in Air Force structures.

A scenario preceeding the list of major structural systems addressed the point that minor and routine maintenance problems had been identified in each of the nine systems. To prevent these minor problems from progressing to a point where they would become critical to the safety,

mission support capability, and overall life expectancy of a structure maintenance action would have to be initiated. The prioritization of maintenance actions was designed into the survey in an attempt to gather data on which major structural systems Air Force facility maintenance managers felt were more susceptable to having minor problems become critical.

Although many technical manuals exist on how to handle specific problems with wood, concrete, and steel structural components, no information was available on how critical these problems are in relation to each other and which require immediate action. Often these manuals seem to assume that a person making structural maintenance decisions has unlimited resources and is concerned with only one problem at a time. In reality, large maintenance organizations have many problems that they must contend with simultaneously. Such is the case with structural maintenance performed by Air Force Civil Engineering. The population of structures is so great and varied and maintenance resources constrained that tradeoffs take place when determining what structural problems should be handled first. The prioritization procedure developed in this thesis is an attempt to quantify some of the tradeoffs made by Air Force facility managers when considering structural maintenance actions under restricted resources.

Population and Sample

Data for this research was collected from Air Force Civil Engineering personnel attending continuing education classes at the Air Force School of Civil Engineering at Wright-Patterson AFB, Ohio. A total of seventy-six surveys were collected from five classes. The classes sampled were as follows:

MGT 415 - Contract Preparation

MGT 420 - Engineering and Environmental Planning (EEP) Management Applications

MGT 425 - Contract Management

MGT 430 - Operations Management Applications

ENG 485 - Contingency Engineering

Personnel from the following U.S. Air Force Bases participated in the survey:

Barksdale AFB, LA
Bolling AFB, Washington, DC
Cannon AFB, WM
Carswell AFB, TX
Castle AFB, CA
Chanute AFB, IL
Charleston AFB, SC
Davis-Monthan AFB, AZ
Dobbins AFB, GA
Dyess AFB, TX
Ellsworth AFB, SD
Fairchild AFB, WA
Forbes Field (ANG), KS
Francis E. Warren AFB, WY
Goodfellow AFB, TX

Griffis AFB, NY
Hahn AB, Germany
Hanscom AFB, MA
Hickam AFB, HI
Hill AFB, UT
Holloman AFB, NM
Homestead AFB, FL
Houston (Ellington AFB), TX
Howard AFB, Panama
Kirtland AFB, NM
K.I. Sawyer AFB, MI
Laughlin AFB, TX
Loring AFB, ME
Lowry AFB, CO
Luke AFB, AZ
Malmstrom AFB, MT
March AFB, CA
Maxwell AFB, AL
McConnell AFB, KS
Nellis AFB, NV
Norton AFB, CA
Osan AB, South Korea
Patrick AFB, FL
Pope AFB, NC
RAF Lakenheath, United Kingdom
RAF Mildenhall, United Kingdom
Ramstein AB, Germany
Reese AFB, TX
Rhein-Main AB, Germany
Robins AFB, GA
Scott AFB, IL
Spangdahlen AB, Germany
Springfield (Capital Airport), (ANG), IL
Tinker AFB, OK

Tyndal AFB, FL
U.S. Air Force Academy, CO
Vandenberg AFB, CA
Whiteman AFB, MO
Wright-Patteron AFB, OH
Wurtsmith AFB, MI

The surveys were grouped into three classes based on the number of years of civil engineering experience. The breakout of surveys versus the number of years of civil engineering experience was as follows:

Years of Civil Engineering Experience	Number of Surveys
0-4	37
5-8	16
9 or more	23
TOTAL	76

The educational level of these three classes was also surveyed. The breakout of surveys returned by degree and experience level was as follows:

Degree Level	Years of Civil Engineering Experience			
	0-4	5-8	over 9	TOTAL
None	0	1	3	4
BS	30	11	10	51
MS	17	4	10	21
TOTAL	37	16	23	76

The number and types of degrees held by those who participated in the survey were as follows:

0-4 Years of Civil Engineering Experience

BS Degree

Architecture	4
Civil Engineering	13
Electrical Engineering	3
General Engineering	2
Industrial Engineering	1
Mechanical Engineering	5
Unspecified on Survey	2

MS Degree		Corresponding BS Degree	
City & Regional Planning	1	Sociology	1
Electrical Engineering	1	Electrical Engineering	1
Industrial Engineering	1	Mechanical Engineering	1
Business Administration	2	Industrial Engineering	1
		Unspecified on Survey	1
Unspecified on Survey	2	Electrical Engineering	1
		Unspecified on Survey	1

5-8 Years of Civil Engineering Experience

No Degree

Surveys Returned	1

BS Degree

Architecture	1
Civil Engineering	5
Electrical Engineering	3
Mechanical Engineering	2

MS Degree		Corresponding BS Degree	
Business Administration	1	Electrical Engineering	1
Civil Engineering	1	Civil Engineering	1
Management	1	Mechanical Engineering	1
Unspecified on Survey	1	Unspecified on Survey	1

Greater Than 9 Years of Civil Engineering Experience

No Degree

Surveys Returned	3

BS Degree

Architecture	4
Civil Engineering	2
Electrical Engineering	1
Unspecified on Survey	3

MS Degree		Corresponding BS Degree	
Business Administration	1	Forest Engineering	1
Civil Engineering	1	Civil Engineering	1
Industrial Engineering	1	Mechanical Engineering	1
Management	3	Architecture	1
		Civil Engineering	2
Public Administration	1	Civil Engineering	1
Unspecified on Survey	3	Unspecified on Survey	3

Surveys were given to persons having degrees other than Civil Engineering and Architects because many of these persons, along with Civil Engineering, migrate up through the ranks of Air Force Civil Engineering to positions where they will have to make decisions in areas where they have little

or no experience. Thus, this survey attempted to capture how Air Force Civil Engineering actually makes structural maintenance decisions and how experience and educational background affects the quality or accuracy of the decisions made.

Systematic Procedure

The prioritization numbers from each of the seventy-six surveys were tabulated by experience group and then reversed to aid analysis. For example, a structural system that scored a one on the survey (handle first) would be awarded nine points on the scoring sheet. Statistically this reversal of the rankings is insignificant. The total number of points for each major structural system was tabulated. These scores were then tested using Friedman's statistical test for comparison of data collected banked on rankings. This statistical test determines which rankings are significant when compared to each other (13).

Rankings were then created for the group of seventy-six surveys as a whole and for each of the three experience groups. Also, the rankings of those holding Civil Engineering degrees were compared to those persons holding other degree types to see if educational background played a role in determining maintenance actions. Once a final list of rankings was completed a model for determining structural maintenance actions was constructed using data found in the

survey. This model included other factors such as the cost of maintenance action, mission impact, estimated cost of repair, and estimated quality of repair.

List of Assumptions

1. Because of real world constraints, structural maintenance decisions are often made in large maintenance organizations such as Air Force Civil Engineering, by persons who may have little or no experience with structural problems.

2. Maintenance resources, especially those in large organizations, are not unlimited. Tradeoffs take place when decision makers attempt to match maintenance resources against organizational demands.

3. Even though technical information exists on how to handle specific structural problems once they are identified maintenance decision makers are often concerned with a series of concurrent maintenance problems that overstretch maintenance resources. This means that even though a solution may be apparent maintenance action may not be taken because of other constraints.

Chapter 5

DATA ANALYSIS

Data gathered by the survey was analyzed using the Friedman Test for nonparametric statistics. This test determines whether or not data gathered in the form of rankings is statistically significant. If the rankings are found to be significantly different then the null hypothesis (H_o) is rejected in favor of the alternative hypothesis (H_a). Multiple comparisons of individual blocks of data can then be made if the null hypothesis is rejected. The raw data gathered by the survey can be found in Appendix B. A sample set of calculations using the Friedman Test can be found in Appendix C.

The hypotheses used to analyze the data were as follows:

> H_o: There was no difference in the structural maintenance requirements of the nine major structural systems identified on the survey as perceived by Air Force Civil Engineering decision makers.
>
> H_a: At least one major structural system has different structural maintenance requirements are perceived by Air Force Civil Engineering decision makers.

These hypotheses were tested at alpha (α) level of 0.20. The alpha level or risk is the probability of making a Type I statistical error which is accepting hypothesis H_a when

hypothesis H_o should really be accepted. Conversely, the beta (β) level or risk is the probability of making a Type II statistical error which is accepting hypothesis H_o when hypothesis H_a should really be accepted. By using a high alpha risk (usually an $\alpha = 0.25$ is the maximum ever used) the probability of making a Type II error (the beta risk) is minimized. For the hypotheses previously stated a high alpha risk means that it is a far more serious error to not perceive different structural maintenance requirements for the nine major structural systems when differences really do exist than to perceive differences when really none exist at all. This means it is far better to overmaintain a structural system when it really does not need maintenance than not to initiate maintenance action on structural systems when action is seriously needed. Granted, significant costs can be incurred by an imprudent inspection and maintenance program (which suggests that a high beta risk should be set instead of a high alpha risk) but if maintenance decision makers generally initiate only pertinent and appropriate structural maintenance then a high alpha risk can be justified.

Different blocks of data gathered by the survey were analyzed using the Friedman Test. First, the maintenance decisions, as measured by the prioritizations, of the entire sample was tested. Second, the maintenance decisions of the three experience groups were tested to see what influence experience had on the maintenance decisions made. Third,

those persons holding a Civil Engineering or Architecture bachelors degree were tested against those persons holding other types of bachelors degrees to see what influence educational background had on the maintenance decisions made. Civil Engineers and Architects, as felt by the author, would have in general more knowledge of structures and structural problems than persons holding other degree types and should be more descriminating in what they perceived a serious structural problem. Finally, Civil Engineers and Architects in each of the three experience groups were tested against those persons holding other bachelors degrees in the same experience groups to see how the interaction of educational background and years experience affected the maintenance decisions made by each group. Figure 5-1 shows the breakout the test groups used in this analysis. The following abbreviations will be used in the subsequent discussions:

- RST - Roof Systems (Timber Beam/Truss Construction)
- RSS - Roof Systems (Steel Beam/Truss Construction)
- RSC - Roof Systems (Concrete Beam/Slab Construction)
- FT - Foundations/Basements (With Timber Members)
- FS - Foundations/Basements (With Steel Members)
- FC - Foundations/Basements (With Concrete Masonry Members)
- WT - Load Bearing Walls/Columns (Timber Construction)
- WS - Load Bearing Walls/Columns (Steel Construction)
- WC - Load Bearing Walls/Columns (Concrete/Masonry Construction)

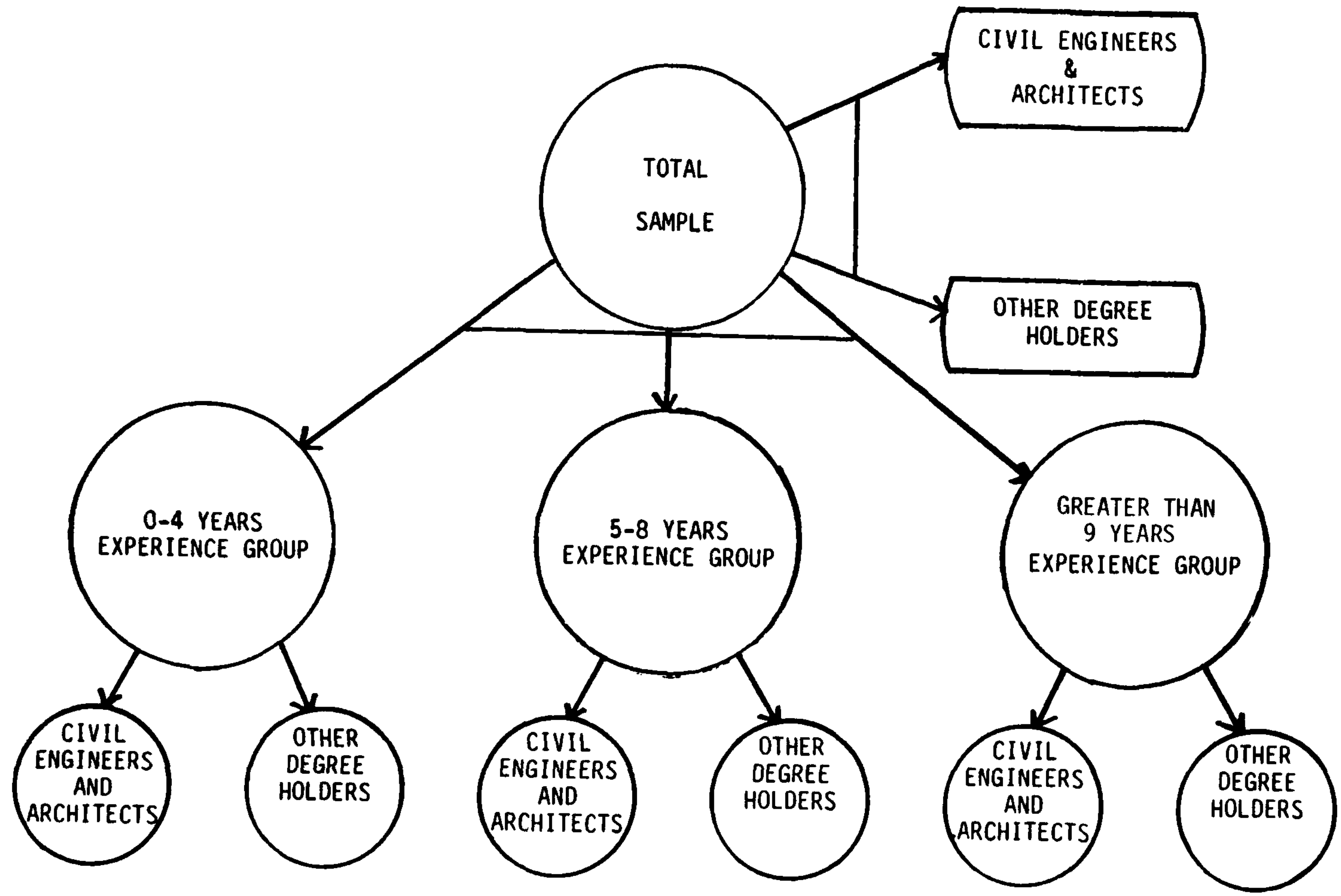
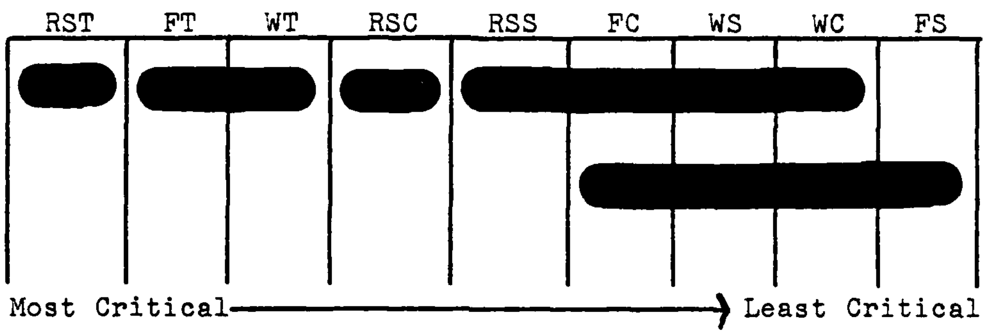


Fig. 5-1

BREAKOUT OF TEST GROUPS FOR ANALYSIS

The total sample, all seventy-six surveys, were analyzed using the hypotheses previously stated. The Friedman Test resulted in the rejection of the null hypothesis and analysis using multiple comparison procedures described in Appendix C yielded the following significant diagram:

TOTAL SAMPLE

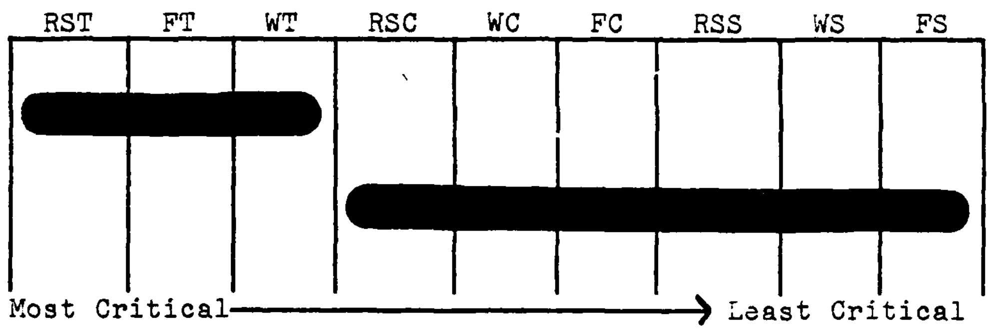


What this diagram shows statistically is those structural systems that were perceived by Air Force Civil Engineering decision makers to be similar in criticality of maintenance needs. Timber Foundations/Basements (FT) were similar in perceived maintenance needs to Timber Load Bearing Walls/Columns (WT). RSS, FC, WS, and WC were all perceived as having no statistical difference in maintenance needs while FC, WS, WC, and FS were also perceived as being similar. RST and RSC were each perceived as not being similar to any other major structural system.

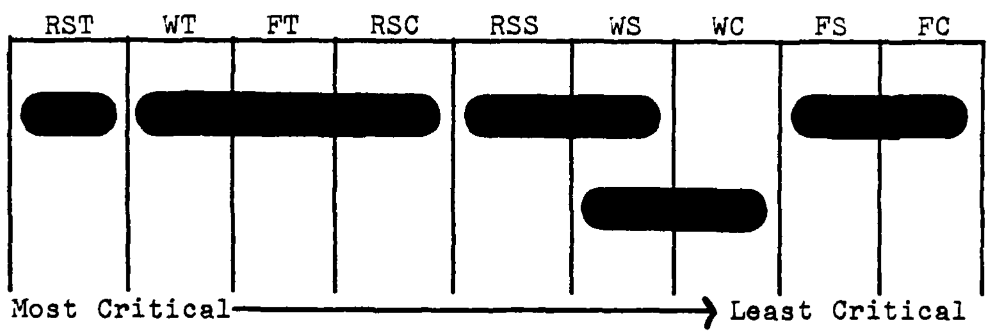
Level of Experience

The three experience groups within the total sample were analyzed using the Friedman Test and the null hypothesis was rejected for each of the three cases. The significance diagrams for each experience group are as follows:

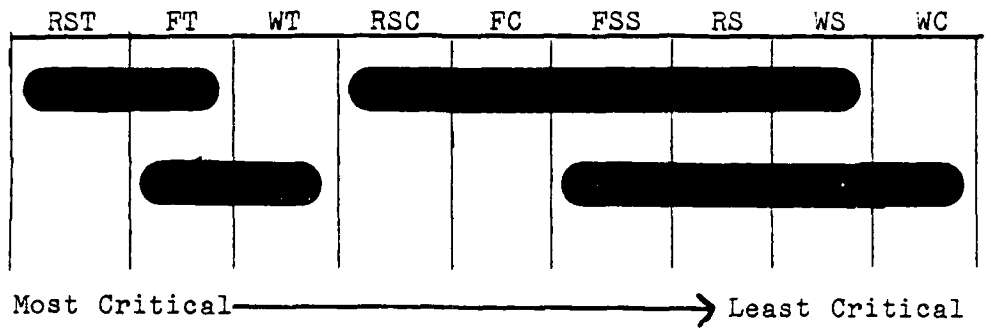
0-4 YEARS EXPERIENCE



5-8 YEARS EXPERIENCE



GREATER THAN 9 YEARS EXPERIENCE

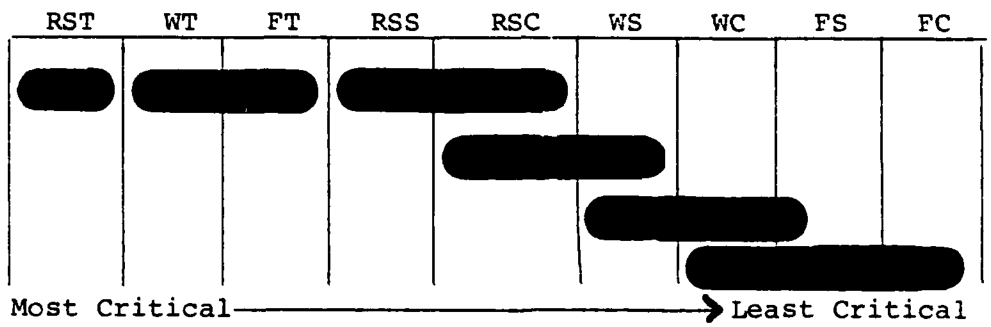


These three diagrams show the maintenance priorities made by Air Force Civil Engineering decision makers based on experience level alone. Timber systems (RST, WT, FT) were determined to be statistically different and most critical for each experience group while steel and concrete systems were viewed as being not statistically different for the 0-4 year group while concrete systems (RSC, FC) were found to be the second worst maintenance problems for the greater than 9 year group. The findings for timber systems are consistent with Chapter 3 while the findings for concrete systems are not. Therefore, proper maintenance decisions are most likely not a function of experience level alone. The effects of educational background on the maintenance priorities made will now be investigated.

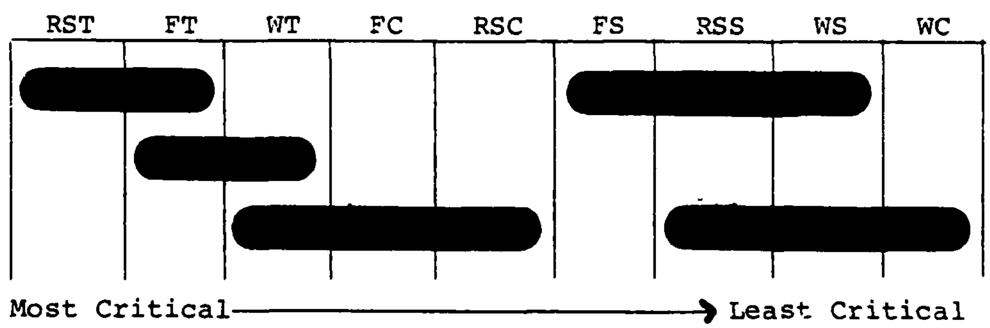
Undergraduate Education

Those persons holding Civil Engineering or Architecture bachelors degrees were tested against those persons holding other bachelors degrees. The null hypohtesis was rejected for each of these groups. The significance diagrams for each of these groups were as follows:

CIVIL ENGINEERS AND ARCHITECTS
IN THE TOTAL SAMPLE



OTHER DEGREE HOLDERS IN
TOTAL SAMPLE

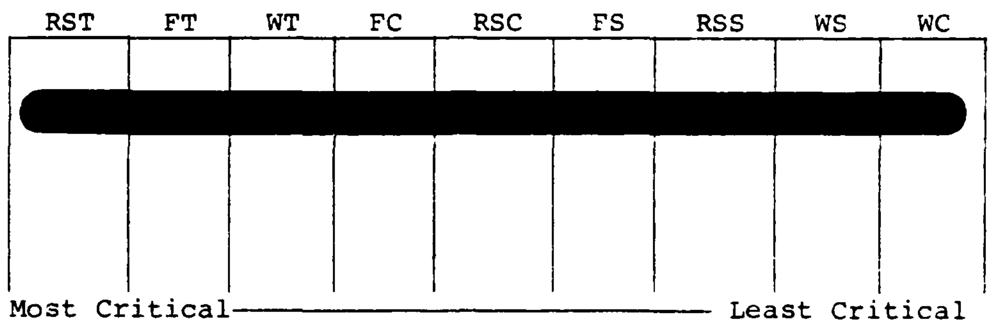


These two diagrams show the maintenance priorities made by Air Force Civil Engineering decision makers based on undergraduate educational background alone. Timber structures were perceived by the Civil Engineers and Architects as being statistically different (consistent with Chapter 3) while the other degree holders rated concrete structures (FC and RSC) as being the second worst maintenance problem (not consistent with Chapter 3) which implies that educational background alone does not ensure proper maintenance decisions. The interaction of experience level and educational background will now be investigated.

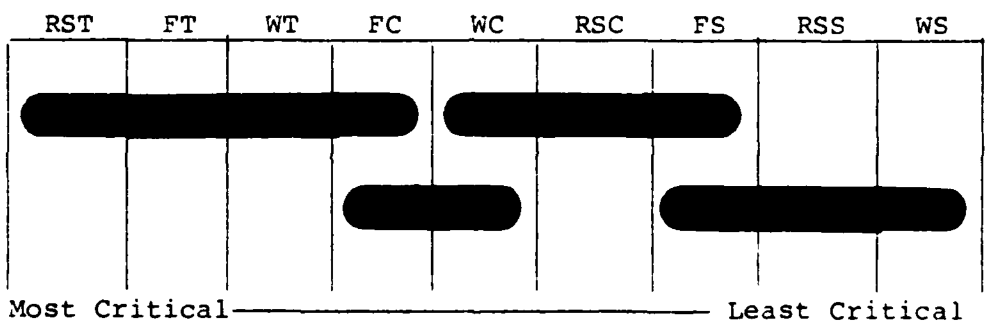
Education and Experience

The final set of tests run on the data attempted to show how the interaction of educatonal background and years experience affected the maintenance decisions made. The null hypothesis was rejected for each of the groups tested except Civil Engineers and Architects with 0-4 years experience. The significance diagrams for each experience group and educational background were as follows:

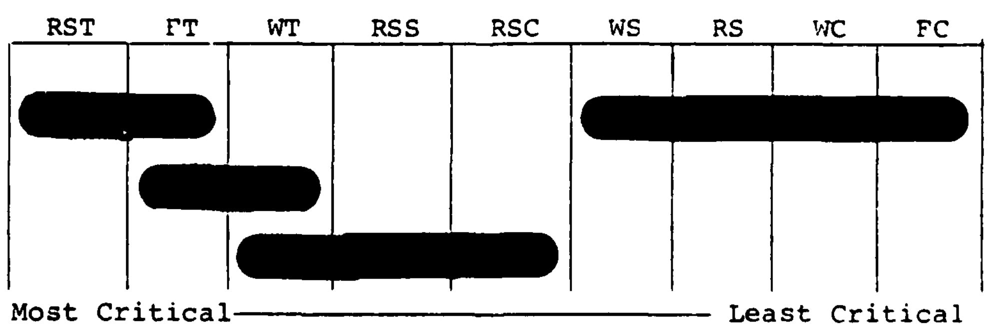
CIVIL ENGINEERS AND ARCHITECTS WITH
0-4 YEARS EXPERIENCE



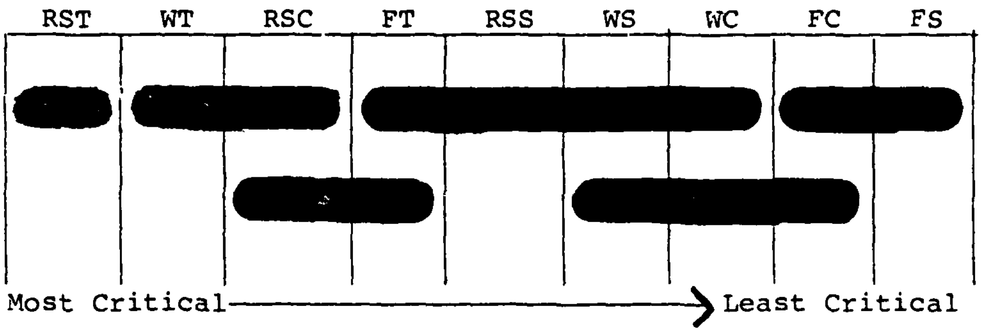
OTHER DEGREE HOLDERS WITH
0-4 YEARS EXPERIENCE



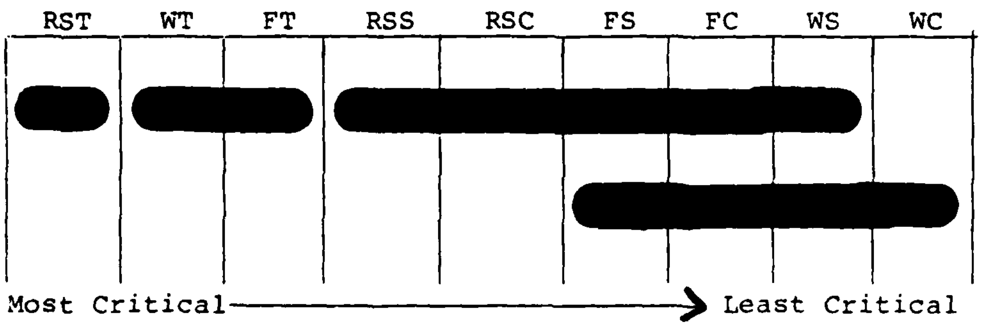
CIVIL ENGINEERS AND ARCHITECTS WITH
5-8 YEARS EXPERIENCE



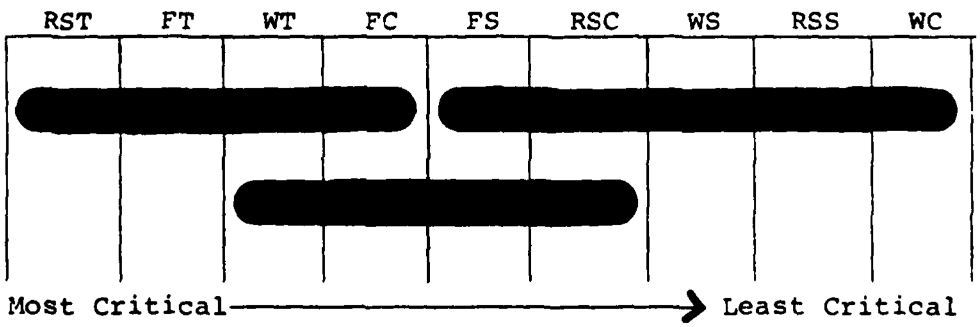
OTHER DEGREE HOLDERS WITH
5-8 YEARS EXPERIENCE



CIVIL ENGINEERS AND ARCHITECTS WITH
GREATER THAN 9 YEARS EXPERIENCE



OTHER DEGREE HOLDERS WITH
GREATER THAN 9 YEARS EXPERIENCE



These six diagrams show the maintenance priorities made by Air Force Civil Engineering decision makers based on the interaction of educational background and experience level. The Civil Engineers and Architects with 0-4 years experience perceive all structural systems as having similar maintenance needs (were not statistically different) while other degree holders with 0-4 years experience did perceive timber (RST, FT, WT) having the worst maintenance needs and concrete (FC, WC, RSC) second worst.

The Civil Engineers and Architects with 5-8 years experience perceived timber (RST, FT, WT) as having the worst maintenance needs while steel (RSS) was second worst. The other degree holders with 5-8 years experience perceived a whole array of priorities with timber (RST, WT) being the worst. Concrete (RSC) was perceived as second worst. One explanation for concrete (RSC) being so high in priority for both 5-8 year groups is that if failure was to occur in a concrete structure the roof system, because of sheer weight and bulk, would pose the most threat to life and property.

The Civil Engineers and Architects with greater than nine years experience perceived timber (RST, WT, FT) as having the worst maintenance needs while roof systems (RSS, RSC) either steel or concrete were second. This concern for the maintenance of roof systems reflects the damage that a sudden collapse of a roof system would cause to life and property. This group also perceived the maintenance of walls (WS, WC)

as being of least priority. The other degree holders with greater than nine years experience perceived maintenance needs greatly different from the Civil Engineers and Architects with the same years experience. This author feels that the maintenance perceptions of the Civil Engineers and Architects with greater than nine years experience are the most consistent with findings of Chapter 3.

Chapter 6

STRUCTURAL MAINTENANCE PROJECT SELECTION MODELS

Introduction

The significance diagrams constructed in Chapter 5 showed that structural maintenance choices made by Air Force facility managers vary greatly with their educational background and years experience. Because of the varied mission of Air Force Civil Engineering, persons without much experience or educational background in structures or structural engineering are often tasked with making structural maintenance decisions. At times many of these structurally inexperienced persons do make the best maintenance decisions but just as often structural maintenance actions are haphazardly initiated (if at all) and minor structural problems progress to the point where serious damage has occurred to the structure.

To illustrate the point of the need for knowledgeable structural maintenance decision makers consider the common problem of roof leaks. In many high population density structures such as offices, shopping areas, and other places of public assembly, roof leaks are usually quickly reported to Civil Engineering because they are extremely bothersome and uncomfortable to work around. Civil Engineering maintenance

crews often quickly repair such problems because the problem has been already identified and customer satisfaction usually depends on how fast the work gets done. But now consider a roof leak in a structure such as a hanger or warehouse with a low population density. These problems are often not quickly identified and many times a bucket is used to keep things from getting "too wet". Hence, it is these structures where the problems tend to go unidentified (to Civil Engineering) for a long period of time and thus increase chances for serious structural damage.

The above discussion considered only the functional use of the building and how users play a role in keeping an eye on structural problems. But now consider roof leaks not only in high density and low density structures but also structures made of the three different materials, wood, steel, and concrete. Chapter 3 identified the major types of deterioration that takes place in these construction materials. Clearly then a roof leak in a wood structure has a distinctly different risk from one in a steel or concrete structure given the same initial degree of severity. Wood, because it is a biological material, begins to rot and decay if left wet for an extended period of time. Steel also will rust and concrete disintegrate if exposed to harmful environments. The question that follows then is "how severe are maintenance problems such as roof leaks in wood, steel, and concrete structures in relation to each other?"

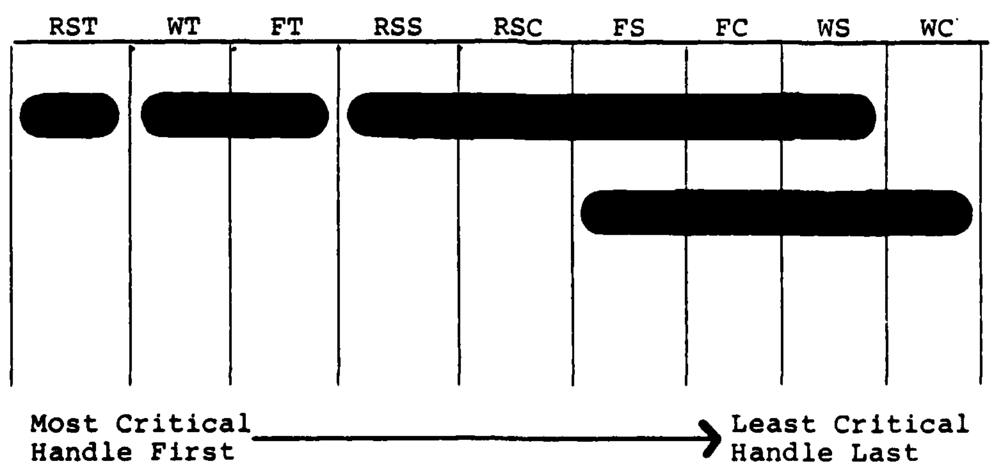
Actually the more complete question to ask is "How severe are maintenance problems in wood, steel, and concrete structures in relation to each other and in what structural systems (roofs, walls, and foundations) do they most often occur?" The engineering textbooks and journals tell us that deterioration of wood, steel, and concrete is distinctly different from each other but not much information was available on what problems should be handled first given that a decision maker is faced with a whole array of structural problems. Thus the survey was initiated to gather data from Air Force Civil Engineering decision makers to see what problems they would handle first given three different types of construction materials (wood, steel, and concrete) and three major structural systems (roofs, walls, and foundations).

Decision Model Number One

This simple model uses the data gathered by the survey as criterion for selecting structural maintenance projects. The basis for decisions in this model will be the perceptions of Air Force Civil Engineering decision makers as to which structures are most susceptable to having small maintenance problems become critical to the strength and safety of a structure. This model closely approximates decisions that would be made if a decision maker had unlimited maintenance resources. The assumption of unlimited resources, especially

for Air Force Civil Engineering maintenance resources, clearly limits the use of this model but does provide a simple model on which to build more complex ones.

Because the significance diagrams developed in Chapter 5 varied greatly with educational background and years experience the author felt that the perceptions of those persons holding Civil Engineering or Architecture bachelors degrees with greater than nine years experience most closely approached the decisions that should have been made given the principles of structural deterioration outlined in Chapter 3. This group felt that roof systems, timber construction were the most susceptable to deterioration with walls timber and foundations timber tied for second. Clearly this concern for timber structures matches the possible problems of timber outlined in that chapter. The significance diagram for this group was as follows:



Because this thesis is attempting to quantify subjective data, scoring models will be used.

> The scoring models are the only models specifically designed to incorporate noneconomic criteria. In addition, the scoring models can operate on input data estimates in the form of subjective estimates provided by knowledgeable people as well as in the form of point or interval estimates [7:214].

Scoring models compute a total project score given a list of criteria and point values. The project having the highest score gets selected first and so on.

The significance diagram for Civil Engineers and Architects with greater than nine years experience shows that roof system timber (RST) was rated significantly different from all other structural systems. Timber walls and foundations (WT, FT) were similar to each other but significantly different from everything else. Assigning a point score to the prioritizations of this group yields the following:

Structural System and Material	Criterion Score (S_{ij})
RST	9 Points
WT, FT	7 Points
RSS, RSC	5 Points
FS, FC, WS	3 Points
WC	1 Point

The point scale (1 point to 9 points) was selected on the basis of having a set of nine major structural systems. If all nine systems were perceived by Air Force Civil Engineering decision makers as being unique and each requiring

special maintenance procedures then a separate score (1 through 9) would have had to be assigned. Therefore, those systems falling on the left side of the significance diagram would be assigned a high S_{ij} score while those on the right a low one.

> The scales for deriving the S_{ij} scores should always reflect actual performance dimensions. To insure that this is the case, the scoring scale can be empirically derived from historical data on prior projects [28:144].

Operation of this model involves identifying the structural problems present in your facilities and then assigning them a point score based on the previous scale. Those systems assigned a high score should get attention first while those assigned a low score last. Ties are left up to the judgement of the decision maker.

Decision Model Number Two

Air Force structural maintenance decision makers must not only be concerned with types of structures (wood, steel, and concrete) and types of structural systems (roofs, walls, and foundations) but also what role a structure plays in support of the Air Force mission. Air Force Regulation 85-1 identifies four levels of work based on mission essentiality. These are:

> (1) Priority I--Mission. Work in direct support of the mission that if not done would reduce operational effectiveness.
>
> (2) Priority II--Safeguard Life and Property. Work needed to give adequate security to areas subject to compromise; to eliminate health, fire, or safety hazards; or to protect valuable property or equipment.

(3) Priority III--Support. Work which helps do the mission or prevents a breakdown of essential operating or housekeeping functions.

(4) Priority IV--Necessary. Not qualifying for higher priority.

-[32:4-2]

Assigning a point score to these priorities yields the following:

Priority Level	Criterion Score (S_{ij})
Priority I	9 Points
Priority II	6 Points
Priority III	3 Points
Priority IV	1 Point

The same scale (1 point to 9 points) is used here to prevent the top score from one criterion variable from dominating over the top score of another criterion variable. This is essential for proper construction of a scoring model. Operation of this model involves the same steps involved in using MODEL # ONE with the additional step of adding in points for mission support priority. For example, a RST having a Priority I rating would receive a total score of 18 points (9 points and 9 points). A WC with a Priority II rating would receive a total score of 7 points (1 point and 6 points).

It should be stated here that these models are only a tool to aid Air Force Civil Engineering decision makers in making structural maintenance decisions. These models are

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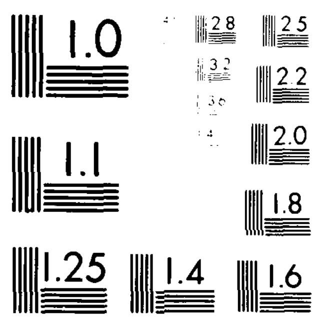


MICROCOPY RESOLUTION TEST CHART

based on the assumption that minor structural maintenance problems have been identified and that action should be initiated to prevent these problems from progressing to a critical state with a critical state being defined as a serious threat to safety of life and property or loss of mission support capability. Structures seriously in danger of collapse should not be evaluated by these models. The model user should use good engineering and management judgement when determining the set of structural maintenance problems that should be prioritized by these models.

Decision Model Number Three

This third and final decision model involves a combination of four criterion variables. The first two of these variables, one for a specific structural system and its material type and another for mission essentiality are exactly the same as those used in MODEL TWO. The third criterion variable has to do with the estimated cost of repair while the fourth deals with the estimated quality of the maintenance work. Both of these variables were added to this model in an attempt to bring some of the concepts of life cycle costing (outlined in Chapter 2) into a structural maintenance decision model.

Scoring models, because they are best designed for noneconomic data, cannot accurately process exact cost data.

To incorporate costs into the scoring model a point value must be assigned to some relative ranges of cost. The author proposes the following system for estimating cost data scores:

<u>COST RANGE</u>	<u>CRITERION SCORE</u> (S_{ij})
Low Cost of Repair Estimate	9 Points
Medium Cost of Repair Estimate	4.5 Points
High Cost of Repair Estimate	1 Point

Higher points are awarded to low cost estimates in an attempt to select projects that minimize costs. Great caution must be exercised here by the model user when estimating costs. Costs should be estimated across the board in the same manner and for bringing structures up to the same level of repair. Some structures, because of construction method, location, or the availability of materials may have an inherently high cost of repair while other structures a relatively low cost of repair when compared to each other. What must be done here instead is to estimate costs with respect to bringing a structure up to some desired level of service and not to how specific costs relate to each other.

In conjunction with cost a fourth criteria was added to this model to capture the quality of maintenance or repair being initiated. As stated in previous chapters, structural maintenance often consists of only a painting or patch job designed to get a structure through its next inspection. Actions such as these provide very short-term benefits at the

expense of the long-term safety and life expectancy of a structure. To help lessen the effects of such maintenance policies the author proposes the following scores:

QUALITY OF MAINTENANCE JOB	CRITERION SCORE (S_{ij})
Lasts greater than 5 Years	9 Points
Lasts 1 year to 5 Years	4.5 Points
Lasts less than 1 Year	1 Point

High quality jobs, as measured by the years a maintenance job is expected to last before it has to be done again, receive greater point scores than do jobs that are undertaken to get a structure in shape for the short run. Again, these scores are attempting to give a higher priority to those maintenance projects that tend to reduce the life cycle costs of a structure.

Thus far, four criterion variables have been identified for use in this model. These are:

1. Structural System and Material
2. Mission Essentialness
3. Cost of Repair
4. Quality of Repair

Scores have been assigned to each item found in the above categories. What must be done now is to assign weights to

each of the four criterion variables in order to rank them in some order of importance. The author proposes the following criterion weights:

CRITERION VARIABLE	CRITERION WEIGHT (W_i)
Structural System and Material	0.30
Mission Priority	0.40
Cost of Repair	0.10
Quality of Repair	0.20

These weights were determined by the author on a subjective basis. They were placed in an order that the author felt would best lead to the selection of projects critical to the mission of the Air Force while keeping in mind the engineering principles of structural deterioration.

Operation of this third model involves computations using the following formula:

$$T_j = \sum_i W_i \, S_{ij}$$

Where T_j = total project score

W_i = criterion weight

S_{ij} = criterion score

The T_j score represents a sum of criterion weights multiplied by their corresponding criterion score. This sum represents an additive index scoring model. The additive index model was used in this thesis because "the additive form of the scoring model produced better correlational results for every

run made in the analysis (7:230)." Both additive index and multiplicative index scoring models were correlated to decisions made using economic index and linear programming models. All had the same data base.

Sample Operation of the Three Proposed Decision Models

Several example cases are provided to illustrate how the decision models work. Table 6-1 shows cost and facility data for five fictitious projects. Tables 6-2, 6-3, and 6-4 show calculations and project priority rankings for MODEL ONE, MODEL TWO, and MODEL THREE respectively.

Comparisons of the models show that all three selected projects A, E, and C as the first three projects to be initiated. MODEL ONE, which has no provisions for dealing with ties, selected both project A and project C as the number one projects. The inability to deal with tie scores is a major shortcoming of this model along with the lack of ability to process mission priority data. MODEL TWO, on the other hand, has the capacity to deal with priority data while ties can be broken (if individual scores for both structural system and material and priority are not identical) by giving a higher ranking to the project with the higher priority score.

MODEL THREE, while ranking projects in the same order that MODEL TWO did, incorporates cost and quality data along with criterion weights in order to award a higher priority

to those projects attempting to maximize quality at minimum costs. Ties in this model should first be broken by going to the highest priority criterion score and then if not broken by going to the highest structural system and material score.

TABLE 6-1

Sample Calculation Data

PROJECT A - Problem/System - Checking and splits of Members in Wooden Roof Trusses

Facility/Mission - Aircraft Shop/Maintenance Building (Priority I)

Estimate Cost - $15,000

Estimated Quality - Greater Than 5 Years of Repair

PROJECT B - Problem/System - Cracking/Spalling of External Concrete Foundation

Facility/Mission - Military Passenger Terminal Building (Priority IV)

Estimated Cost - $7,000

Estimated Quality - 1-5 Years of Repair

PROJECT C - Problem/System - Checking of Members in Wooden Roof Trusses

Facility/Mission - Base Gymnasium (Priority III)

Estimated Cost - $21,000

Estimated Quality - 1-5 Years of Repair

PROJECT D - Problem/System - Deteriorated Masonry Walls

Facility/Mission - Accounting and Finance Building (Priority II)

Estimated Cost - $26,000

Estimated Quality - Greater than 5 Years of Repair

PROJECT E - Problem/System - Roof Leaks in a Steel Frame Structure

Facility/Mission - Base Supply Warehouse (Priority I)

Estimated Cost - $4,000

Estimated Quality - Less Than 1 Year of Repair

TABLE 6-2

Project Rankings Using Model One

PROJECT	STRUCTURAL SYSTEM AND MATERIAL	CRITERION SCORE (S_{ij})
PROJECT-A	Roof System Timber (RST)	9
PROJECT-B	Foundations Concrete (FC)	3
PROJECT-C	Roof System Timber (RST)	9
PROJECT-D	Walls Concrete (WC)	1
PROJECT-E	Roof System Steel (RSS)	5

PROJECT RANKINGS

DO FIRST - PROJECTS A and C (tie)

DO SECOND - PROJECT E

DO THIRD - PROJECT B

DO FOURTH - PROJECT D

TABLE 6-3

Project Rankings Using Model Two

PROJECT	STRUCTURAL SYSTEM AND MATERIAL	CRITERION SCORE(S_{ij})	MISSION PRIORITY	CRITERION SCORE(S_{ij})	TOTAL SCORE
PROJECT-A	Roof System Timber (RST)	9	I	9	18
PROJECT-B	Foundations Concrete (FC)	3	IV	1	4
PROJECT-C	Roof System Timber (RST)	9	III	4	12
PROJECT-D	Walls Concrete (WC)	1	II	6	7
PROJECT-E	Roof System Steel (RSS)	5	I	9	14

PROJECT RANKINGS

DO FIRST - PROJECT A

DO SECOND - PROJECT E

DO THIRD - PROJECT C

DO FOURTH - PROJECT D

DO FIFTH - PROJECT B

TABLE 6-4

Project Rankings Using Model Three

PROJECT A

CRITERION	CRITERION SCORE(S_{ij})	CRITERION WEIGHT(W_i)	S_{ij} X W_i
Structural System and Material (RST)	9	0.30	2.70
Mission Priority (I)	9	0.40	3.60
Estimated Cost Rating - (Medium)	4.5	0.20	0.45
Estimated Quality Of Repair (Greater Than 5 Years)	9	0.20	1.80

$T_j = \sum S_{ij} \text{ X } W_i = 8.55$

PROJECT B

CRITERION	CRITERION SCORE(S_{ij})	CRITERION WEIGHT(W_i)	S_{ij} X W_i
Structural System and Material (FC)	3	0.30	0.90
Mission Priority (IV)	1	0.40	0.40
Estimated Cost Rating - (Low)	9	0.10	0.90
Estimated Quality of Repair (1-5 Years)	4.5	0.20	0.90

$T_j = \sum S_{ij} \text{ X } W_i = 3.10$

TABLE 6-4 (Continued)

PROJECT C

CRITERION	CRITERION SCORE(S_{ij})	CRITERION WEIGHT(W_i)	S_{ij} X W_i
Structural System and Material (RST)	9	0.30	2.70
Mission Priority (III)	3	0.40	1.20
Estimated Cost Rating - (Medium)	4.5	0.10	0.45
Estimated Quality of Repair (1-5) Years	4.5	0.20	0.90

$$T_j = \sum S_{ij} \text{ X } W_i = 5.25$$

PROJECT D

CRITERION	CRITERION SCORE(S_{ij})	CRITERION WEIGHT(W_i)	S_{ij} X W_i
Structural System and Material (WC)	1	0.30	0.30
Mission Priority (II)	6	0.40	2.40
Estimated Cost Rating - (High)	1	0.10	0.10
Estimated Quality of Repair	9	0.20	1.80

$$T_j = \sum S_{ij} \text{ X } W_i = 4.60$$

TABLE 6-4 (Continued)

PROJECT E

CRITERION	CRITERION SCORE(S_{ij})	CRITERION WEIGHT(W_i)	S_{ij} X W_i
Structural System And Material (RSS)	5	0.30	1.50
Mission Priority (I)	9	0.40	3.60
Estimated Cost Rating - (Low)	9	0.10	0.90
Estimated Quality of Repair (Less Than 1 Year)	1	0.20	0.20

$$T_j = \sum S_{ij} \times W_i = 6.20$$

PROJECT RANKINGS

DO FIRST - PROJECT A

DO SECOND - PROJECT E

DO THIRD - PROJECT C

DO FOURTH - PROJECT D

DO FIFTH - PROJECT B

If ties are still not broken then priority should be given to the project having the highest expected quality rating and then, if still not broken, to the highest cost rating.

Limitations of the Models

It must be stated here that any decision model is a tool used by decision makers to quantify critical variables in some structured and systematic way to help evaluate decision alternatives. A model's output can only be as accurate as the information input. The proposed models in this thesis are ones that have been designed to quantify four major facility maintenance variables: structural system and material, mission support capability, cost of repair, and quality of repair. These variables are the ones, as felt by this author, that most often contribute to the overall structural maintenance costs of a structure. Other persons may or may not agree with these model variables or may have others that they would like to add to tailor the models to their needs. The important point to note is that the decision model that is finally constructed can only be as accurate as the information input. Hence, the process used to construct the model must attempt to measure and quantify the actual decision variables and constraints that decision makers face in real world situations. Users of these models should feel free to modify them according to their specific needs provided they use a systematic procedure that attempts to quantify the variables that they would like to add.

Chapter 7

SUMMARY, CONCLUSIONS, AND FUTURE RESEARCH

Summary

The objectives of this research were:

1. Identify what specific structural systems are most critical to overall facility life and readiness.

2. Compare the structural maintenance decisions made by Air Force facility managers to published engineering experience and theory on structural deterioration and maintenance.

3. Develop a prioritization procedure for determining which structural maintenance projects should be done first given restructed maintenance resources.

A brief summary of each of the above objectives follows:

In designing the survey nine major structural systems were chosen. As stated in Chapter 4, broad and general structural systems were identified on the survey rather than specific ones because the list of possible specific structural problems would be too long to quantify. In reality, all structural systems of a building (roof, walls, foundations) are critical to the safety of a structure. What the survey attempted to show was what structural systems, if any, are

perceived as having minor maintenance problems become critical. First, the survey and subsequent analysis revealed that a decision makers educational background and number of years experience greatly influenced perception of the more critical structural problems.

Because structural maintenance perceptions varied greatly with educational background and years experience, it was felt by the author that the decisions made by Civil Engineers and Architects with greater than nine years experience more closely followed the structural maintenance theory outlined in Chapter 3. The decisions made by this group were used in the construction of the project selection models found in Chapter 6.

Another important finding was that Civil Engineers and Architects with zero to four years experience treated the structural maintenance requirements of the nine major structural systems as being not statistically different (accept the null hypothesis, H_o). Persons with other bachelors degrees with zero to four years experience did perceive some structural systems as having different maintenance needs. This was a totally unexpected finding because Civil Engineers and Architects are the persons who most often deal with structures of all types and should have the most knowledge on how each type of structural system can fail.

The prioritization procedures that were developed in the form of scoring models attempted to quantify four aspects of structural maintenance decisions.

1. Structural system type and material
2. Mission essentiality
3. Cost of repair
4. Quality of repair

Three models were developed to show how each of these concerns can influence the final decisions made. Choice of model depends on how much data is available. An important point to note is that these models can incorporate concerns other than the ones mentioned above if a decision maker can rate and weight his additional concerns. The four criteria used in this thesis were felt by the author to be the ones most often encountered by structural maintenance decision makers.

Conclusions

The tremendous variety of structures found in the Air Force coupled with constrained maintenance resources make proper structure maintenance programs difficult to implement on a large scale. What should be done instead is to concentrate most of one's structural maintenance resources on those structures that are more susceptible to having minor problems become critical. But there seems to be a great variation in what structural systems Air Force Civil Engineering decision makers feel are the most maintenance critical. This variation

was a function of educational background and years experience. It is hoped that this research has shed some light on the problem of structural maintenance decision making in the Air Force and that we can get away from haphazard maintenance choices, or worse, non-decisions which allow minor problems to eventually produce serious damage.

Future Research

1. Survey a larger sample of Air Force Civil Engineering decision makers (especially Civil Engineers and Architects with zero to four years experience) to see if the findings are similar to this research.

2. Develop a procedure for determining or forecasting when structural maintenance actions should be initiated given the type of structure, maintenance history, occupancy, climate, and other factors.

APPENDIX A

SAMPLE SURVEY

AFIT GRADUATE THESIS SURVEY

AFSC ________________ JOB DESCRIPTION (civilians) ________________

Degrees BS ________________

MS ________________

other ________________

Home Base ________________

Years of Civil Engineering Experience ________

Rank or GS Level ________

Maintenance problems have been identified in each of the nine major structural systems listed below. At present, these problems are not urgent and are all at the same relative level of deterioration. Assume that the risk to life and property (including the risk to mission readiness) is equal for <u>all</u> nine cases. Please rank these structural systems in the order that you, as a decision maker for your maintenance organization, would initiate maintenance action on to prevent the identified problem from becoming critical to a structures safety, mission support capability, and overall life expectancy.

1 = most critical, handle first 9 = least critical, handle last

___ Roof Systems (Timber Beam/Truss Construction)

___ Roof Systems (Steel Beam/Truss Construction)

___ Roof Systems (Concrete Beam/Slab Construction)

___ Foundations/Basements (With Timber Members)

___ Foundations/Basements (With Steel Members)

___ Foundations/Basements (With Concrete/Masonry Members)

___ Load Bearing Walls/Columns (Timber Construction)

___ Load Bearing Walls/Columns (Steel Construction)

___ Load Bearing Walls/Columns (Concrete/Masonry Construction)

APPENDIX B

RAW DATA

NOTE - Data appears in this appendix opposite of the way it was collected on the original survey. For example:

Most Critical, Handle First		Least Critical, Handle Last
Priority #1	→	Priority #9
SCORE = 9 POINTS		SCORE = 1 POINT

SURVEY #	RST	RSS	RSC	FT	FS	FC	WT	WS	WC	YEARS EXPERIENCE	BACHELORS DEGREE
1	9	7	8	6	5	4	3	2	1	2	Architecture
2	9	6	7	8	2	1	5	4	3	4	Architecture
3	7	8	9	2	1	3	4	5	6	2	Architecture
4	6	5	4	2	1	3	8	7	9	1	Unspecified
5	4	6	7	3	2	1	9	5	8	1	Unspecified
6	7	4	1	9	6	3	8	5	2	2	Electrical Eng
7	9	3	4	8	2	7	6	1	5	1	Electrical Eng
8	2	1	3	9	7	8	6	4	5	2	Electrical Eng
9	4	2	3	1	8	9	7	5	6	2	Industrial Eng
10	7	1	4	9	3	6	8	2	5	2	Electrical Eng
11	2	5	7	4	1	6	3	9	8	2	Unspecified

SURVEY #	RST	RSS	RSC	FT	FS	FC	WT	WS	WC	YEARS EXPERIENCE	BACHELORS DEGREE
12	8	2	5	9	3	6	7	1	4	1	Sociology
13	9	7	8	5	2	4	6	1	3	4	Mechanical Eng
14	9	3	6	8	2	5	7	1	4	2	Unspecified
15	7	2	5	9	3	6	8	1	4	1	Industrual Eng
16	9	3	6	8	5	2	7	1	4	1	Electrical Eng
17	5	3	2	1	8	9	4	6	7	1	Mechanical Eng
18	9	7	8	6	4	5	3	1	2	1	Mechanical Eng
19	2	3	4	7	8	9	1	5	6	1	Mechanical Eng
20	9	3	6	7	1	4	8	2	5	1	Mechanical Eng
21	7	4	1	9	6	3	8	5	2	4	Mechanical Eng
22	9	3	6	7	1	4	8	2	5	2	Architecture
23	6	4	5	9	7	8	2	1	3	2	General Eng
24	3	2	1	7	8	9	4	5	6	3	General Eng
25	9	7	5	8	4	1	6	3	2	4	Civil Eng
26	6	5	4	3	2	1	9	8	7	1	Civil Eng
27	2	3	1	7	9	8	6	4	5	1	Civil Eng
28	3	2	1	9	8	7	6	5	4	1	Civil Eng

SURVEY #	RST	RSS	RSC	FT	FS	FC	WT	WS	WC	YEARS EXPERIENCE	BACHELORS DEGREE
29	7	8	9	2	3	1	5	6	4	2	Civil Eng
30	7	8	9	1	2	3	4	6	5	1	Civil Eng
31	4	5	6	1	2	3	7	8	9	1	Civil Eng
32	9	3	6	5	1	2	8	4	7	1	Civil Eng
33	9	6	3	8	5	2	7	4	1	2	Civil Eng
34	9	5	3	8	6	1	7	4	2	2	Civil Eng
35	9	6	3	7	4	1	8	5	2	4	Civil Eng
36	7	8	1	1	3	2	4	6	5	0	Civil Eng
37	3	1	2	9	5	7	8	4	6	4	Civil Eng
38	9	8	7	6	5	4	3	2	1	7	None
39	9	6	5	8	4	3	7	2	1	7	Civil Eng
40	9	3	6	8	2	5	7	1	4	8	Mechanical Eng
41	9	8	7	3	2	1	6	5	4	5	Electrical Eng
42	6	4	5	3	1	2	9	7	8	5	Unspecified
43	9	5	6	7	2	1	8	4	3	8	Civil Eng
44	8	4	5	7	1	2	9	6	3	6	Civil Eng
45	8	5	9	7	2	1	6	3	4	5	Civil Eng

SURVEY #	RST	RSS	RSC	FT	FS	FC	WT	WS	WC	YEARS EXPERIENCE	BACHELORS DEGREE
46	8	9	6	3	4	7	1	2	5	5	Civil Eng
47	7	4	1	9	6	3	8	5	2	5	Civil Eng
48	9	6	5	8	4	1	7	3	2	5	Architecture
49	9	3	4	8	2	6	7	5	1	7	Electrical Eng
50	7	2	9	1	2	3	4	5	6	7	Electrical Eng
51	9	8	7	3	2	1	6	5	4	6	Electrical Eng
52	9	4	7	5	1	2	8	3	6	5	Mechanical Eng
53	8	4	3	7	1	2	9	6	5	6	Mechanical Eng
54	3	2	1	9	8	7	6	5	4	17	Mechanical Eng
55	9	3	2	8	4	5	7	6	1	11	Unspecified
56	9	7	8	5	4	6	2	1	3	11	Unspecified
57	9	7	8	6	5	4	3	1	2	14	Unspecified
58	9	4	3	8	7	6	2	1	5	14	Forest Eng
59	9	1	3	8	2	4	7	5	6	15	Architecture
60	9	5	8	7	4	3	6	1	2	10	Civil Eng
61	8	5	2	7	4	1	9	6	3	11	Civil Eng

SURVEY #	RST	RSS	RSC	FT	FS	FC	WT	WS	WC	YEARS EXPERIENCE	BACHELORS DEGREE
62	3	1	2	9	7	8	6	4	5	16	Civil Eng
63	9	3	6	8	2	5	7	1	4	14	Civil Eng
64	7	4	1	9	6	3	8	5	2	11	Electrical Eng
65	9	3	6	7	1	2	8	5	4	14	Unspecified
66	7	1	4	9	3	6	8	2	5	16	Unspecified
67	9	7	8	3	1	2	6	4	5	26	Unspecified
68	6	5	4	3	2	7	9	8	1	30	None
69	1	2	6	7	9	8	3	5	4	30	None
70	1	2	3	7	8	9	4	5	6	12	None
71	8	6	7	5	4	9	3	1	2	18	Architecture
72	9	6	3	7	4	1	8	5	2	13	Architecture
73	9	6	5	8	4	2	7	3	1	14	Architecture
74	9	8	7	3	2	1	6	5	4	13	Architecutre
75	7	4		9	6	3	8	5	2	14	Civil Eng
76	9	6	7	2	1	3	8	4	5	15	Civil Eng

APPENDIX C

SAMPLE CALCULATIONS USING THE FRIEDMAN TEST

The calculations found in this appendix are the ones used to create the significance diagram for the total sample of surveys. The hypothesis used to analyze the data collected for the total sample of surveys were the same as stated in Chapter 5:

H_0: There was no difference in the structural maintenance requirements of the nine major structural systems identified on the as perceived by Air Force Civil Engineering decision makers.

H_a: At least one major structural system has different structural maintenance requirements as perceived by Air Force Civil Engineering decision makers.

In order to use the Friedman Test two assumptions must be made about the data:

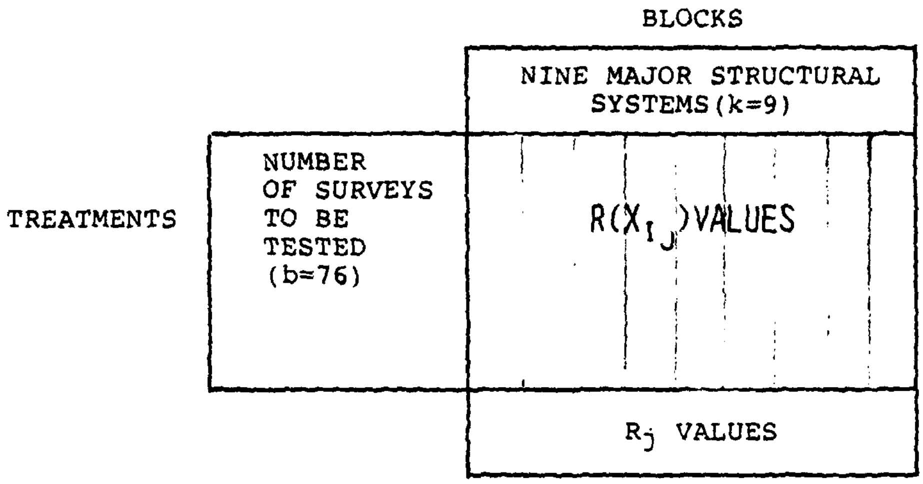
1. The b k-variate random variables are mutually independent. For the data tested in this set of calculations b equals the number of surveys (=76) while k equals the number of major structural systems (=9).

2. Within each block, block being defined as the set of rankings (1 through 9) found on each individual survey, the perceptions or observations are ranked according to some criterion of interest. In this thesis the criterion of interest was the perception of Air Force Civil Engineering decision makers about the need for structural maintenance on specific structural systems.

The first calculation to perform is:

$$R_j = \sum_{i=1}^{b} R(X_{ij})$$

for $j = 1,2,...k$ where $R(X_{ij})$ equals the ranks found within individual treatments. The following diagram should help clarify what is meant by the above formula.



The R_j values for the total sample of surveys were as follows:

RST	RSS	RSC	FT	FS	FC	WT	WS	WC
543	339	370	469	289	313	471	300	309

The first test statistic to calculate is the term A_2 given by the formula:

$$A_2 = \sum_{i=1}^{b} \sum_{j=1}^{k} [\bar{R}(X_{ij})]^2$$

If no ties are allowed to occur within individual treatments then the formula for A_2 simplifies to:

$$A_2 = \frac{bk(k+1)(2k+1)}{6}$$

For this thesis, because no ties were allowed to occur within individual treatments, the simplified formula yields:

$$A_2 = \frac{(76)(9)(9+1)(2(9)+1)}{6} = 21,660$$

The second test statistic to calculate is the term B_2 given by the formula:

$$B_2 = \frac{1}{b} \sum_{j=1}^{k} R_j^{\,2}$$

For this run of the Friedman Test:

$$B_2 = \frac{1}{76} \left[(543)^2+(339)^2+(370)^2+(469)^2+(289)^2+(313)^2+(471)^2+(300)^2+(309)^2 \right] = 17,835$$

The final test statistic to calculate is the term T_2 given by the formula:

$$T_2 = \frac{(b-1)\left[B_2 - \frac{b(k)(k+1)^2}{4} \right]}{A_2 - B_2}$$

For this run of the Friedman Test:

$$T_2 = \frac{(76-1)\left[17,835 - \frac{76(9)(9+1)^2}{4} \right]}{21,660-17,835} = 14.40$$

The decision rule for the Friedman Test is as follows:

Reject H_o at the level α if T_2 exceeds the $1-\alpha$ quantile of the F distribution where $k_1 = (k-1)$ and $k_2 = (b-1)(k-1)$

The alpha (α) level equals 0.20 for reasons stated in Chapter 5 and:

$$k_1 = (k-1) - (9-1) = 8$$

$$k_2 = (b-1)(k-1) = (76-1)(9-1) = 600$$

From standard F distribution statistical tables using the k_1 and k_2 values the $(1-\alpha)$ quantile value equals 1.41. Since T_2 is greater than 1.41 reject H_o. Therefore we conclude

that at least one of the nine major structural systems has different structural maintenance requirements as perceived by Air Force Civil Engineering decision makers.

Multiple comparisons may be made between individual blocks if the first part of the Friedman Test results in rejection of the null hypothesis. Treatments i and j are considered different if the following inequality is satisfied:

$$|R_j - R_i| > t_{1-\alpha/2} \left[\frac{2b(A_2-B_2)}{(b-1)(k-1)}\right]^{\frac{1}{2}}$$

where A_2 and B_2 are the test statistics previously calculated and where $t_{1-\alpha/2}$ is the $1-\alpha$ quantile value of the standard t statistical distribution with (b-1)(k-1) degrees of freedom. R_i and R_j are any two of the previously calculated R_j values. For multiple comparisons of this run of the Friedman Test:

$$|R_j - R_i| > t_{1-\frac{.20}{2}} \left[\frac{2(76)(21,660 - 17,835)}{(76-1)\ (9-1)}\right]^{\frac{1}{2}}$$

$$|R_j - R_i| > t_{0.90} \left[969.06\right]^{\frac{1}{2}}$$

$$|R_j - R_i| > 1.282 \left[969.06\right]^{\frac{1}{2}}$$

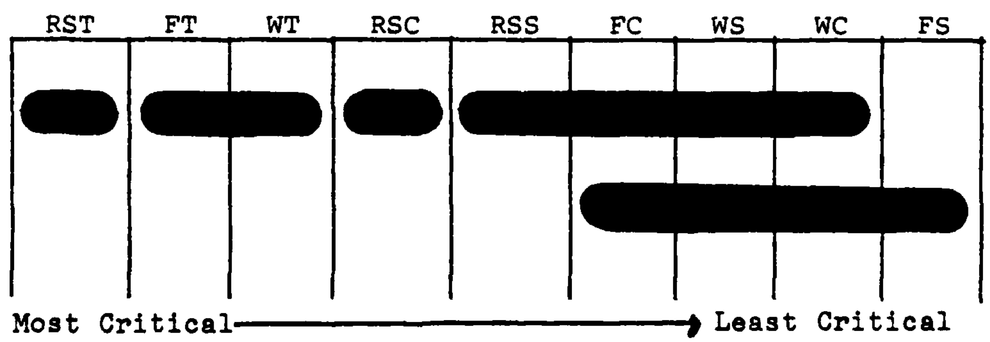
$$|R_j - R_i| > 39.91$$

Therefore, any two R_j values whose difference is greater than 39.91 can be considered statistically different. Using the previously calculated R_j values the following difference table can be constructed.

MAJOR STRUCTURAL SYSTEM AND R_j SCORE	STATISTICALLY DIFFERENT FROM THE FOLLOWING STRUCTURAL SYSTEMS
RST(543)	RSS, RSC, FT, FS, FC, WT, WS, WC
RSS(339)	RST, FT, WT, RSC, FS
RSC(370)	RST, RSS, FT, WT, FC, WS, WC, FS
FT(469)	RST, FT, WT, RSC, RSS
FC(313)	RST, FT, WT, RSC
WT(471)	RST, RSC, RSS, FC, WS, WC, FS
WS(300)	RST, FT, WT, RSC
WC(309)	RST, FT, WT, RSC

Conversely, the following bubble or significance diagram can be constructed showing those systems not statistically different connected by a solid dark swath or bubble.

TOTAL SAMPLE



This same procedure was used to create all the significance diagrams found in Chapter 5. Additional information on the Friedman Test can be found in reference 13.

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